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Internal Water Potential of an Engelmann Spruce Stand in Relation to Soil and Atmospheric Factors

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INTERNAL WATER POTENTIAL OF AN ENGELMANN SPRUCE STAND IN RELATION TO SOIL AND ATMOSPHERIC FACTORS

by

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ABSTRACT

Internal Water Potential of an Engelmann

Spruce Stand in Relation to Soil

and Atmospheric Factors

by

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Utah State University, 1973

Major Professor: Dr. George E. Hart
Department: Forest Science

The primary objective of this study was to determine the degree of correlation between internal water potential of Engelmann spruce trees and selected environmental factors. The secondary objective of the study was to determine the effect of summer precipitation, both in meadow and forested sites, on the soil drying cycle.

Four study plots (each roughly 154 square meters) under spruce cover and two study plots (100 square meters) in a small meadow were established. At each spruce plot, a thermocouple psychrometer was installed at one meter above the ground on the north side of three selected, mature Engelmann spruce trees. Thermocouple psychrometers were installed at 5, 15, and 30 cm depths in the soil at the meadow plots and at 15, 30, 45, and 90 cm depths at the spruce plots. A tensiometer and two soil temperature thermocouples were installed near the thermocouple psychrometers at each of the plots but at 15, 30, 45, and 90 cm soil depths. Throughfall gages were placed at each plot to obtain an

estimate of rainfall which was not intercepted by the canopy but which fell to the forest floor.

Gross precipitation was measured by a 20.3 cm diameter recording gage located at the meadow. Global radiation and wind were recorded at the meadow area also. Air temperature and relative humidity were recorded in wooden shelters. One shelter was located at the meadow area and one was located in the vicinity of the four spruce plots.

Except for wind, weather parameters were recorded continuously. Wind movement was totalized on a digital counter and recorded on data sheets when needed. Psychrometric, pressure chamber, and soil data were obtained according to two schedules. Diurnal measurements of trunk water potential in six trees and independent variables were made during seven days in the summer months of 1971. Seasonal measurements of trunk water potential in twelve trees and independent variables were done at periodic intervals during the summer averaging every three to four days. Data to evaluate the effect of summer precipitation on the soil drying cycle was obtained periodically the summer of 1970 and concurrently (for the most part) with tree water potential measurements during 1971.

Significant findings of this study included the following: as shown by analyses of variation of the data, within-season variations of tree water potential (by psychrometer and pressure chamber measurements) were statistically significant. In other words, fluctuations in water potential with time were large enough that they could not have been due to chance alone.

On an hourly basis for seven cycles of diurnal measurements, daily peaks in wind movement corresponded roughly with trunk water potential

minima, peak radiation occurred about two hours before water potential minima, and maximum vapor pressure deficits corresponded closely to water potential minima. Diurnal fluctuations in water potential of small understory branches, as determined by the pressure chamber, did not correlate well with weather factors.

Seasonally, trunk water potential appeared to be highly correlated with fluctuations in vapor pressure deficit and less correlated with global radiation and wind. Soil factors such as matric potential and temperature were not correlated with trunk water potential. Correlations between water potential determined by the pressure chamber and environmental factors were not consistent. Pressure chamber values of water potential, however, did correlate roughly with trunk water potential during the latter half of the summer of 1971.

By multiple regression analysis, a predictive equation was devised to predict trunk water potential on a daily and on a seasonal basis. With diurnal input data, radiation, vapor pressure deficit, and a transformation of vapor pressure deficit were significant variables. The model explained 81 percent of the diurnal variation in trunk water potential. Evaluation of the model with seasonal data input showed only one variable, vapor pressure deficit, highly significant. With seasonal data, 72 percent of the variation in trunk water potential was explained.

Analysis of 18 rainstorms which occurred during two summers of study showed that roughly 0.25 cm of rain must fall before interception storage of a spruce canopy is satisfied and measurable amounts of rain can fall to the forest floor. Variability among sample catches of a

given storm was great, apparently reflecting the irregular nature of the overmature spruce canopy. On the average, 96 percent of rainfall from storms between 0.00 and 0.13 cm, 70 percent between 0.13 and 1.3 cm, and 38 percent between 1.3 and 2.5 cm was intercepted. The influence of rain on soil matric potential was restricted to the first 45 cm of soil at the spruce plots with no substantial increase of matric potential before the onset of fall rains. The effect of rain on matric potential of soil in the meadow was more pronounced. The matric potential of the 5, 15, and 30 cm depths fluctuated greatly. A temporary increase in matric potential of these depths following summer storms was noted while more marked increases in matric potential were measured after heavier fall rains.

The major conclusions made as a result of this study are (1) relative vapor pressure in the trunks of Engelmann spruce changes markedly from hour-to-hour and from day-to-day during the summer months, (2) trunk water potential as measured by thermocouple psychrometers is functionally related to atmospheric factors of radiation, wind, and vapor pressure deficit, (3) fluctuations in trunk water potential with weather factors imply a causal relation with transpiration, (4) precipitation during the summer months modifies soil matric potential--but only in the shallow profiles, (5) matric potential fluctuations in the meadow areas are extreme (from saturation to low as - 40 bars) and would impose a serious threat to the water economy of young Engelmann spruce seedlings established in such meadows, and (6) Peltier type thermocouple psychrometers are useful instruments for investigation of the soil-plant-atmosphere continuum in field situations.

(152 pages)

INTRODUCTION

Nature of the problem

Little is known about the internal water relations of large trees. Engelmann spruce, a species which grows to great heights and inhabits the higher and cooler elevations of the Intermountain Region, is of such ecologic importance that efforts are being made to mathematically model its energy, nutrient, and water budgets. Understanding the internal water relations of Engelmann spruce, as affected by changing environmental factors, will assist in predicting changes in the nature of the ecosystem as a result of man's activities--whether they be weather modification, removal of wood products, or management for increased water savings.

Hypothesis

As substantiated to some degree, one expects to find highest water potentials in the soil (low tensions) with progressive decreases (higher tensions) in water potential with increasing height in the tree (from roots to trunk, to branches, and to the atmosphere). The actual steepness of such gradients depends upon availability of soil water, rate of water entry into the root system, and the rate of transpirational loss which, itself, is heavily dependent upon atmospheric conditions. With the cool summer air temperatures, and availability of large reserves of soil water characteristic of the study area, it was hypothesized that water potentials measured in the soil and trees would generally be high and indicative of low stress conditions. Because summers are typically

dry in the Engelmann spruce region in the Intermountain area, a rapid drop in soil water potential was expected for shallow soil horizons under the influence of direct evaporation. Some fluctuations, or adjustments of water potential gradients in the soil-plant-atmosphere continuum were expected as changing weather patterns influenced transpiration rates, and transpiration rates in turn affected internal water stresses.

Objectives

The primary objective of this study was to determine the degree of correlation between the internal water potential of Engelmann spruce trees and selected environmental factors. In order to more clearly understand the variations in internal water potential, within-season and diurnal trends were to be investigated. A linear effect model of within-season and diurnal trends was to be determined in order to quantitatively and statistically access the correlation of environmental factors to internal water potential.

A secondary objective of the study was to determine the effect of summer precipitation, both in open meadow and forested sites, on the soil drying cycle. Determination of relative magnitudes of summer precipitation in relation to throughfall, depth of penetration of rain into the soil, and fluctuations of water potential produced by alternately wetting and drying of the soil, was expected to help in understanding the soil-plant-atmosphere system in Engelmann spruce.

REVIEW OF LITERATURE

Literature cited in this review covers (1) silvics of the Engelmann spruce-subalpine fir type, (2) theory and measurement of water potential in plant and soil systems, and (3) measurement of water potential in Engelmann spruce and other forest trees. The information acquired by this review contributed greatly to design, implementation, and interpretation of this study.

Silvics of the Engelmann Spruce-Subalpine Fir Type

Ecological description

The Engelmann spruce-subalpine fir type is the climax development of spruce and fir found in the Intermountain Region. These stands are able to replace themselves with time (barring catastrophic fire) with subalpine fir frequently becoming the dominant species in composition. In climax stands the age-class distribution approaches an all-aged condition made up of small, even aged groups. Some stands of over-mature, all-aged spruce-fir are found at the Utah State University College Forest (T. W. Daniel, personal communication, 1972).

The climate of the Engelmann spruce-subalpine fir type is typically cool and humid. A compilation in Fowells (1965) shows the spruce-fir habitat in western United States characterized by temperature extremes (-46 to 32 C), high annual precipitation (64 to 89 cm in the Central Rocky Mountains), and frost-free periods ranging from 30 to 60 days. Deep winter snowfalls of three meters or greater are common in the central Rocky Mountain Region.

Engelmann spruce (Picea engelmannii Parry) may be the major component in the Engelmann spruce-subalpine type providing time is allowed for mortality of shorter-lived subalpine fir. Mineral soil favors Engelmann spruce, but subalpine fir will usually reproduce more successfully. Besides subalpine fir Engelmann spruce may be found growing with other species. In the central Rocky Mountains, species associated with Engelmann spruce may include lodgepole pine (Pinus contorta Dougl.), interior Douglas-fir (Pseudotsuga menziesii var. glauca Franco), blue spruce (Picea pungens Engelm.) and aspen (Populus tremuloides Michx.) at lower elevations, and may include whitebark pine (Pinus albicaulis Engelm.), limber pine (Pinus flexilis James), and subalpine fir (Abies lasiocarpa Nutt.) at the higher elevations (Fowells, 1965). At the Utah State University College Forest, where this study was conducted, the species composition of two sections (518 ha.) averaged 19 percent Engelmann spruce, 65 percent subalpine fir, 2.8 percent lodgepole pine, 12.1 percent aspen, and 1.1 percent Douglas-fir and limber pine (Moore, 1971).

Engelmann spruce is shade tolerant, although its common associate, subalpine fir, appears to survive even heavier shade (Bates, 1923). Engelmann spruce is sensitive to high solar intensities, and shading will greatly decrease mortality of field planted seedlings (Ronco, 1970a, 1970b).

Engelmann spruce grows well on moderately deep, well drained silt and clay loams (Roe, Alexander, and Andrews, 1970; Fowells, 1965) and on heavy soils (Daniel, 1962). Engelmann spruce also grows well in some instances on shallow soil (Oosting and Reed, 1952; Hodson and Foster,

1910). One may assume, given other factors are favorable, that Engelmann spruce can grow on a wide variety of soil types.

Distribution

Engelmann spruce is a widely distributed species. It is found in nine western states and two Canadian provinces. Its range stretches from Alberta and British Columbia to New Mexico and Arizona (Fowells, 1965). It is a major species component of high elevation watersheds in the Rocky Mountain Region (Fowells, 1965; and Daniel, 1962). In the central Rocky Mountain Region, Engelmann spruce and subalpine fir can be found at an elevational range of 2700 to 3400 meters with some stands extending as low as 2400 meters and as high as 3500 meters (Bates, 1923; Pearson, 1931, as cited by Fowells, 1965).

Growth and development

Engelmann spruce and subalpine fir require a mineral soil seedbed for optimum germination and establishment. Subalpine fir is able to germinate on a wider variety of surfaces than Engelmann spruce and so its seedbed requirements are somewhat less exacting (Daniel, 1962; Roe, Alexander, and Andrews, 1970). Successful establishment of spruce and fir depends upon other factors besides a plentiful supply of seed and proper seedbed conditions. Shade, summer precipitation, soil texture and air temperature may be important variables (Roe, Alexander, and Andrews, 1970; Ronco, 1970a, 1970b; and Daniel, 1962).

Cone production in both Engelmann spruce and subalpine fir is rated good by LeBarron and Jemison (1953) in northern Idaho and Montana with subalpine fir somewhat the better producer of the two species. At the Utah State University College Forest (Daniel, 1962) for a 26

year record, Engelmann spruce produced five good, ten fair, and eleven poor cone crops. Subalpine fir produced four good, six fair, and sixteen poor cone crops. These results are divergent from those shown by LeBarron and Jemison (1953) perhaps pointing out the importance of local climatic conditions on the physiology of the cone production cycles.

Early growth of Engelmann spruce is typically slow. Roeser (1924) found that even the most vigorous seedlings produced roots to a maximum depth of only 1.1 cm in one year. In the Medicine Bow Mountains of Wyoming (Oosting and Reed, 1952), spruce saplings only 1.2 to 1.8 meters tall were 45 to 70 years old.

Engelmann spruce is one of the largest trees found in high forested watersheds within its range. Under good growing conditions it may average 45 to 76 cm in diameter and 24 to 30 meters tall at maturity (Hodson and Foster, 1910). Measurement of 64 one-tenth hectare plots at the Utah State University College Forest showed Engelmann spruce to reach an average height of 27 meters at a diameter of 51 cm (Moore, 1971). It is a long-lived tree and reaches maturity in about 300 years (Alexander, 1958a; Fowells, 1965). Subalpine fir reaches maturity in about 250 years (Alexander, 1958b).

Evapotranspiration

Publications concerning evapotranspiration of Engelmann spruce and subalpine fir are limited in number. Some early work attempted to determine by the phytometer method the relative transpiration rates and soil water depletion capabilities of Engelmann spruce, lodgepole pine, and ponderosa pine (Bates, 1923; Pearson, 1924). The usefulness of

these studies is indeterminate as they were conducted in a greenhouse where the environment around the seedlings was apt to differ greatly from natural conditions. Besides this, environmental gradients in phytometers are not likely to be the same as found around seedlings growing in the field.

A direct attempt to compare soil water depletion of Engelmann spruce with other vegetation types was reported by Brown and Thompson (1965) in Colorado. Engelmann spruce was intermediate in water use when compared to aspen and grassland. Soil water depletion by Engelmann spruce was estimated to be 3.2 mm per day for a 2.4 meter soil depth. Soil water depletion patterns of Engelmann spruce and the relation of depletion to environmental factors have been studied at the Utah State University College Forest (Eaton, 1971). From the first year of data, evapotranspiration was estimated to vary from 1.5 to 6.6 mm per day (a two meter soil profile) for selected periods of about seven to fourteen days. Average evapotranspiration for the growing period was 33 cm. Soil water depletion over time periods of about two weeks was closely related with atmospheric variables (radiation, wind, and vapor pressure deficit).

The heat pulse method of estimating sap velocities has provided an indirect means of studying transpiration in trees in relation to changing environmental conditions. The heat pulse method is not new, appearing to be first described by Huber and Schmidt (1936, as cited by Zimmerman, 1971). The method has also been clarified and described by Marshall (1958), Swanson (1962), and Swanson and Lee (1966). Swanson (1967) made sap velocity measurements in pole-sized Engelmann spruce and lodgepole pine trees at the Fraser Experimental Forest, Colorado. Inferences

about seasonal transpiration rates included (1) transpiration occurred throughout the year, (2) peak values were observed in May, (3) day to day variation in transpiration was shown in response to weather factors during the summer months only, and (4) winter transpiration rates were small. Sap velocity was shown to exhibit a definite diurnal pattern which also varied according to time of year and species and seemed to be correlated with weather conditions.

Transpiration at various positions in the crown of five subalpine fir trees was measured by Stark (1969). Findings of this study showed (1) the difference in transpiration between the top and bottom of the trees varied with season, exposure, and time of the day, and (2) in August some mechanism reduced transpiration beyond what would have been expected with concurrent air temperature and relative humidity.

Stomatal behavior is important in regulating transpiration rates which, in turn, limit sap velocities; unfortunately, informative studies of stomatal behavior in Engelmann spruce and other conifers are not in the literature. Hinkley and Ritchie (1970) measured stomatal aperture, transpiration, and water stress in two Pacific silver fir trees (Abies amabilis Forbes). They measured stomatal apertures by a pressure infiltration method and reported that, on two sunny days, stomatal apertures increased from bottom to top of the trees. On a rainy day they observed that stomata opened, stem water potential (measured by the pressure chamber) increased from a previous low of -9 bars to -3 bars, and sap velocity decreased from 7.5 to 3.5 cm per hour. These results are indicative of the effect of high humidities in reducing the transpiration rate and lowering internal water stress in the trees. Obviously more information about stomatal reactions to various changing factors such as air

temperature, wind, radiation, and precipitation is needed. While the results of Hinkley and Ritchie (1970) are interesting, it is a matter of conjecture whether or not such relationships would be found in either Engelmann spruce or subalpine fir.

Theory and Measurement of Water Potentials in Plant and Soil Systems

Theoretical considerations

The water potential concept has its origin in thermodynamic theory. This section, admittedly brief and simplified, will serve as an introduction to theory involved in measuring the energy properties of water in the soil-plant-atmosphere system. Many references are available in basic thermodynamics as it applies to measurement in biological systems. The reader is referred to Spanner (1964) for detailed treatment of this subject.

Many thermodynamic terms are found in the literature and clarification of these individually and in relation to one another will provide an easier understanding of the water potential concept. Energy states of water in the soil and plant system can be explained in terms of Gibbs free energy. Gibbs free energy is an extensive thermodynamic property along with mass, volume, area, and heat capacity (Spanner, 1964). When considered as the component water in the soil or plant, it is an expression of the capacity of water to do work. Inversely, Gibbs free energy is the amount of work required to remove water from one location to another under standard conditions. According to Spanner (1964), Gibbs free energy is but a narrowly defined portion of the free energy concept and is preferred by biologists because it corresponds to

cellular conditions where work is necessary to produce volume changes against a constant environmental pressure. A decrease in Gibbs free energy provides the maximum useful work under conditions of constant temperature and pressure.

The chemical potential dictates the direction of spontaneous diffusion of water, analagous to temperature determining the direction of heat flow and electrical potential determining the direction in which electric current will flow (Spanner, 1964). The difference in chemical potential between pure water and water in the plant or soil system provides the driving force for water and solute movement under constant conditions of temperature, pressure, and gravity.

The term water potential has been more widely accepted than chemical potential among physiologists and biochemists (Slatyer and Taylor, 1960; Taylor and Slatyer, 1962; and Spanner, 1964). A further consideration of plant and soil water potential and their respective components will be considered in the next section.

Another thermodynamic term which is often used is activity or relative activity of water. Activity refers to the tendency of water to move in the system (Brown, 1970) while relative activity of water refers to the ratio of vapor pressure of water in the system to vapor pressure of pure water (Korven and Taylor, 1959). In soil water, for instance, relative activity may be thought of as relative humidity or relative vapor pressure (Taylor, Evans, and Kemper, 1961). An important assumption in this concept is that the chemical potential of water is in equilibrium with the chemical potential of pure water vapor at a given temperature and pressure (Slatyer, 1967).

With the above stated assumption and knowledge of the universal gas law, an equation can be derived relating water potential to relative vapor pressure. This is the well-known Kelvin equation:

$$\mu_{water} - \mu_{pure\ water} = \Psi = \frac{RT}{V} \ln \frac{e}{e_o} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where,

μ is chemical potential,
Ψ is water potential expressed as a negative value,
R is the universal gas constant,
T is the absolute temperature in K,
e is the actual vapor pressure of water in the soil or plant system,
e_o is the vapor pressure of pure, free water, and
V is the partial molal volume of water (enables water potential to be expressed in pressure rather than energy units).

Treatment of the Kelvin equation can also be found in Brown (1970), Rawlins and Dalton (1967), Box (1965), Lang (1967), and Rawlins (1971). A simplified mathematical derivation of the Kelvin equation can be found in Slatyer (1967).

Component potentials

The chemical potential of water in the soil or plant system differs from pure water. If solute molecules are present, they exert pressure on adjacent water molecules, and the chemical free energy or water potential is reduced (Dainty, 1969; Brown, 1970). This component is referred to as the osmotic potential of the system. Repulsive forces between water molecules will be increased or decreased depending upon whether pressures are above or below the atmospheric pressure (Brown, 1970). This component is denoted as the pressure potential of the system. If the plant or soil system contains soil-liquid or gas-liquid interfaces, water molecules in the interfaces will be subject to forces not found in pure water systems (Dainty, 1969) and water potential will be reduced.

This component is denoted as the matric potential of the system. Additional components which may affect the water potential of a system are the effects of temperature and gravity. Water potential is decreased when temperature is decreased because of loss of free energy from the water molecules (Brown, 1970). Gravitational force is also a component potential and is important in affecting flow processes when considerable distances are involved.

Energy Gradients and Flow Theory in the Plant-Soil-Water System

Water flow in the soil is primarily dependent upon gradients in matric potential (Dainty, 1969). Since in saline soils (low osmotic potential) the solutes move with soil water, the osmotic component makes no contribution to flow (Dainty, 1969; Slatyer, 1967). In non-saline soils the matric potential gradient is approximately equal to the water potential gradient when the effect of gravity is negligible; the water potential gradient may be considered as the driving force (Dainty, 1969). The gravitational potential is more important in saturated soils than in unsaturated soils (Slatyer, 1967).

Water movement across the root surface and into the xylary elements is not clearly understood. Dainty (1969) considers flow to be proportional to the gradient in water potential since the reflection coefficient of solutes (α) is close to unity. The reflection coefficient is unity if membranes are completely nonpermeable to solutes. Slatyer (1967) suggests that α may be less than unity for some solutes. If membranes were largely permeable, that is if solutes moved with the water, the pressure potential gradient would be the driving force for water movement.

Water movement in the xylem has received considerable attention; and as a result, the transpiration cohesion-pull theory has been proposed. The physical mechanisms seem clear and acceptable to most workers (Dainty, 1969), and since no differentially permeable membranes are involved ($\alpha = 0$), flow is primarily a function of the pressure potential gradient (Dainty, 1969; Slatyer, 1967; Zimmerman, 1971). The current controversy concerning the transpiration cohesion-pull theory is whether or not water is stable enough to prevent cavitation when stresses are imposed on it by bending and stretching of the stem (Dainty, 1969).

Water movement from the leaf to the external air is driven by a gradient in water vapor concentration (Dainty, 1969; Slatyer, 1967). Resistance to flow may be high with small stomatal apertures, thick leaf cuticles, and thick boundary layers in the air.

Theory and development of the thermocouple psychrometer

Spanner (1951) is generally given credit for development of the thermocouple psychrometer, an instrument capable of sensing extremely small changes in relative vapor pressure. Following this development two kinds of thermocouple psychrometers were developed, both of which operate on the same principle as the wet bulb-dry bulb psychrometer (Rawlins, 1971). The psychrometer developed by Richards and Ogata (1958) requires water to be manually placed on the wet junction; the other type of psychrometer places water on the wet junction by thermoelectric means (the Peltier effect) and is sometimes referred to as the Peltier psychrometer. Both types of psychrometers employ the Seebeck effect to generate an electromotive force when a temperature

differential is created between junctions of two dissimilar metals. The electromotive force can be measured either indirectly with a galvanometer or directly with a millivolt potentiometer.

Some papers on the theoretical aspects of Peltier psychrometers include Peck (1968, 1969), and Rawlins (1971). Design considerations which materially contributed to the author's work were found in Box (1965), Brown (1970), and Dalton and Rawlins (1968). A reader interested in construction, calibration, and application of Peltier psychrometers is referred to Brown (1970). Calibration technique can be found in Box (1965), Hoffman and Splinter (1968), Klute and Richards (1962), Korven and Taylor (1959), Lang (1967), Brown (1970), and Campbell (1971). Development of water potential prediction equations incorporating temperature effects on psychrometric response is found in Meyn and White (1972). Rawlins and Dalton (1967) give excellent treatment to possible experimental errors in measurement of soil water potential by the psychrometric technique.

Theory and development of the pressure chamber

The pressure chamber (or "bomb" as it is sometimes called) was first used extensively by Scholander et al. (1965) for the purpose of determining plant water potential. Briefly, this approach requires that stems of plants be stripped of bark for a centimeter or two, placed in a steel pressure chamber with the cut end exposed, pressure applied inside the chamber at a regulated rate, and a reading taken when sufficient pressure has been applied to force xylem water out through the end of the stem (Scholander, 1965; Boyer, 1967; Kaufman, 1968; Pierpoint, 1967; Waring and Cleary, 1967; Wiebe, 1971).

Some disagreement among authors exists as to the exact meaning of pressure chamber measurements, the appropriate terminology and what components of water potential are represented. Pressure chamber measurements have been called "internal moisture pressure" (Pierpoint, 1967), "xylem sap tension" (Hickman, 1970), "twig" or "stem water potential" (Wiebe, 1971; Kaufman, 1968; Hodges and Lorio, 1970), and "sap pressure" (Boyer, 1967). It seems clear, at least, that the pressure necessary to cause exudation of xylem water is approximately the same (absolute value) as the negative pressure or tension which existed in the stem immediately prior to cutting.

Pressure chamber determinations of water status in trees are cited by Zimmerman (1971) as evidence of negative pressures. Certainly, then, one component measured by the pressure chamber is the pressure potential. Boyer (1967) states that the pressure chamber measures the non-osmotic portion of total plant water potential and it does not distinguish between matric and hydrostatic forces. He claims that pressure chamber readings are primarily a function of leaf water potential. Pierpoint (1967), Wiebe (1971), and Waring and Cleary (1967) consider pressure chamber readings to be a function of negative pressures in the xylem.

Pressure chamber determinations of stem water potential may vary considerably from concomitant psychrometric determinations (Boyer, 1967; Kaufman, 1967). Boyer (1967) suggests that, in plants having osmotic potentials of -2 to -3 bars, the osmotic component should be added to the pressure potential--as determined by the pressure bomb--to give a reasonable estimate of total stem water potential.

Even with the various interpretations of meaning of pressure chamber readings, the method holds promise for providing an economical and simple way to determine relative plant water status. As such, some standardization in technique is needed for pressure chamber determinations to be compared from one location to another. It is clear from examination of the literature that some standard should exist for length of stem extending beyond the chamber, time between cutting and measuring samples, and exposure of samples to insolation. The possible errors with such sampling variation are considered next.

Four common sources of error in pressure chamber determinations are repeatedly mentioned in the literature. First is the time between collecting and making pressure chamber determinations. Pierpoint (1967) suggests that samples should be taken as soon as possible; Waring and Cleary (1967) claim that samples can be cut up to five minutes before placing them in the pressure chamber, and Hickman (1970) says that storage up to eight hours in plastic bags results in little change in tensions. If excessive time elapsed before making a pressure chamber determination, water potentials would be expected to be too high--less tension than normal--(Pierpoint, 1967; Waring and Cleary, 1967). This, of course, would not be the case if samples were exposed long enough that they were physically desiccated. Different lengths of exposure to sunlight before placing samples in the pressure chamber may constitute a possible error (Waring and Cleary, 1967). Variable stem length outside of the pressure chamber appears to be universally recognized as a possible source of error (Wiebe, 1971; Waring and Cleary, 1967; Boyer, 1967). Boyer (1967) found the effect of stem length to be approximately 0.2-0.3 bar additional pressure (per cm). Because of

this, Wiebe (1971) cautions against attempts to make a second cut of the stem before placing it in the chamber as it may result in excessively high water potentials. Other possible errors include "overshoot of pressure" application caused by resistance to pressure in the xylem (Kaufman, 1968) and leakage through open xylem elements in stems that have a soft center, or pith.

Water Potentials in Engelmann Spruce and Other Forest Trees

Study of water potentials in Engelmann spruce or other forest vegetation has not been done to any large degree. Some data are available for selected portions of the soil-plant-atmosphere system in these vegetation types, but there is little known about the system as a whole.

Seasonal variations

Lindsay (1971) studied the annual cycle of leaf water potential in Engelmann spruce and subalpine fir by use of the Schardakov dye method. Leaf water potentials were higher during the summer than during the winter. Lindsay attributed leaf water potentials of -35 to -15 bars in winter to the effect of drying winds and cold, dry soils. On a seasonal basis he found leaf water potential to be closely related to vapor pressure of the air. Wind also appeared to affect leaf water potential by lowering leaf temperature and removing thick, moist-air boundary layers.

Diurnal variation

Diurnal variation in stem water potential has been studied by Waring and Cleary (1967) and Hinkley and Ritchie (1970). With the pressure chamber Waring and Cleary (1967) found a marked diurnal variation in internal water potential at the upper crown level of a 25 meter

Douglas-fir tree. A high water potential of -8 atmospheres was reached at 0600 hours, a low of -19 atmospheres was reached at 1430 hours, and by late afternoon water potentials had returned to morning values. Hinkley and Ritchie (1970) measured water potential with the pressure chamber throughout the crowns of two Pacific silver fir trees. They found minimum stem water potentials at about 1200 hours for both north and south sides of the trees. Stem water potentials were also shown to be related with environmental conditions. In response to a rainy day the authors measured increased stem water potentials (-9 to -3 bars) and reduced sap velocity.

Water potential gradients

Of the limited available literature Wiebe et al. (1970) seem to have made the only attempt to measure water potential gradients throughout the soil-tree-atmosphere system. Twig, branch, and trunk water potentials of Juniperus, Ulmus, Elaeagnus, and Acer were measured with implanted thermocouple psychrometers. Soil water potentials were also measured. Pressure chamber determinations of stem water potential and psychrometer sample chamber estimations of leaf water potential served as a check for validity of measured water potentials with implanted psychrometers. In general, water potential gradients were shown to comply with values expected by theory; highest water potentials were measured in the soil with progressive decreases in water potential shown with increasing height in the tree. Leaf water potentials were lowest. The authors state that with a decrease in transpiration at night water potential increased and water potential gradients became less steep.

The preceding review does not attempt to cover all of the information available on silvics of Engelmann spruce, water potential theory,

and water potential measurements in trees, but it does summarize what the author feels is essential to understanding the following discussion. Certain studies will be mentioned again where their results and conclusions can be compared to the reported findings of this study.

DESCRIPTION OF THE STUDY AREA

Physical Description

The study area is located in the Bear River Basin which encompasses northeastern Utah, southeastern Idaho, and southwestern Wyoming. The actual plots are located in Section 21, Township 13 North, Range 4 East (Salt Lake Meridian) at the Utah State University College Forest. Elevation at the study area is approximately 2600 meters. The general aspect of the land is northeasterly with a range of slopes from level to approximately 20 percent.

Vegetation

Composition and structure of the overstory

The overstory of the forested areas, with the exception of bands of quaking aspen, consists of uneven-aged Engelmann spruce and subalpine fir ranging from about 20 to 90 cm in diameter and from 10 to 40 meters in height. The predominant species in the overstory at the study area is Engelmann spruce with some subalpine fir and an occasional Douglas-fir. Figure 1 shows a view of the vegetation in which the large Engelmann spruce dominants can be seen in the background with subalpine fir appearing mostly as codominants in the canopy.

Composition of the understory

The predominant growth of vegetation in the understory of the coniferous stands is subalpine fir of many ages. Such advanced reproduction is patch-like in distribution, and except for at the larger openings

Figure 1. View of vegetation at the study area. Slope in the foreground has a northeasterly aspect.

in the canopy, it is suppressed, and of poor vigor. A few broadleaf plants and grasses are found under the canopy where there is sufficient light for growth. Under the dense parts of the canopy the ground surface is nearly devoid of broadleaf vegetation and covered only with a layer of needles, branches, and cone debris.

Composition and nature of meadow vegetation

Intermixed with stands of conifer and aspen at the study site are areas of meadow (Figure 1). Some common broadleaf genera found in the meadow areas include Potentilla, Lupinus, Geranium, Aster, Delphinium, and Achillea. Some less commonly found genera include Hydrophyllum, Senecio, Lomatium, and Rosa. An abundant brome grass (Bromus) is also found in the meadows along with numerous annuals.

Figure 2 shows the typical pattern and density of vegetation in the meadow areas in and adjacent to the study area. Note the amount of bare and rough-textured ground surface. The ground is continuously disturbed by burrowing of mountain pocket golphers (Thomomystapoides, Richardson). Incidental to the objectives of the study, the effect of two year's exclosure to sheep grazing is easily seen in Figure 2. To the left of the fence, the sheep have consumed most of the broadleaf vegetation.

Rooting patterns

Rooting depth information was obtained at the study area by excavating a soil pit in a meadow and in a conifer stand. The north face of the pit at the conifer site was carefully mapped using a string grid and 1.3 cm mesh screen. The large roots (those having cross-sectional areas greater than 5 mm) were concentrated in the first 30 cm of soil

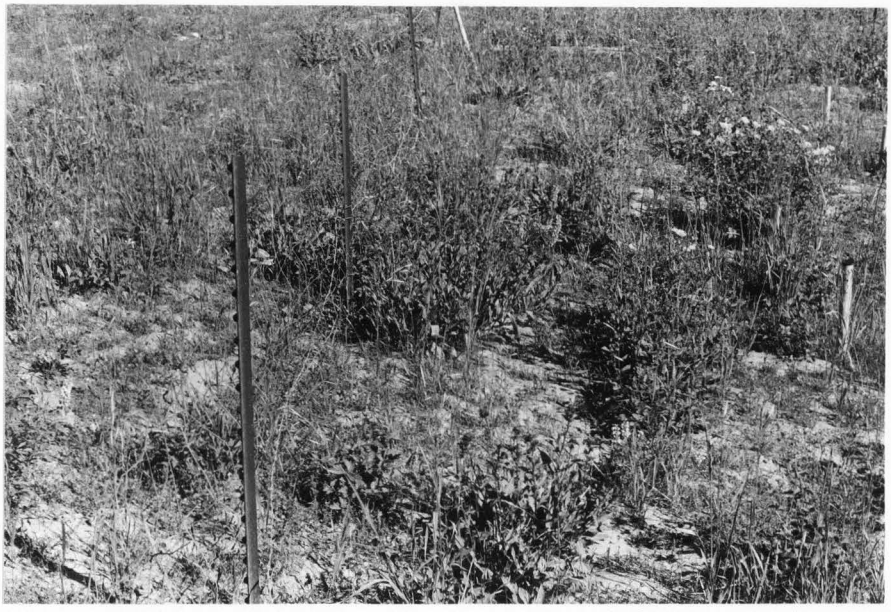

Figure 2. Typical meadow vegetation. The metal fence posts are approximately 1.5 meters high. The dense clumps of vegetation are Aster and Potentilla.

(Table 1). Most of the fine roots were found in the first 75 cm of soil with the greatest concentration in the 15 to 30 cm increment.

Table 1. Root distribution in an Engelmann spruce stand at the Utah State University College Forest

	Mean (8 samples)		Range (8 samples)	
Depth increment from surface	Cross-sectional area roots >5 mm diameter	No. of roots ≥1 mm and ≤5 mm diameter	Cross-sectional area roots >5 mm diameter	No. of roots ≥1 mm and ≤5 mm diameter
(cm)	(cm^2)		(cm^2)	
0 to 15	0.31	3.9	0 - 1.33	0 - 11
15 to 30	1.69	6.1	0 - 3.29	2 - 10
30 to 45	0.03	1.5	0 - 0.20	0 - 5
45 to 60	0.12	1.3	0 - 0.50	0 - 3
60 to 75	0.17	1.6	0 - 1.33	0 - 5
75 to 90	0.00	0.8		0 - 4
90 to 105	0.00	0.3		0 - 2
105 to 120	0.00	0.3		0 - 2

A sample consisted of all roots encountered in a string-gridded area of 15 by 15 cm dimensions (225 cm^2).

Only an occasional root was found below 120 cm. Rooting patterns of vegetation at the meadow pit were not mapped; however, roots were found mainly in the 0 to 30 cm soil profile and no roots were found below about one meter depth.

Climate

The climate of the study area is unique compared to the high elevation areas in other parts of the central Rocky Mountain Region.

Winters are cold with snow accumulations of two meters or greater and summers are typically dry (instead of rainy) and cool. Snow may persist on the ground through the first week of July, or later.

Precipitation

Only two complete annual precipitation records are currently available for the study site. Annual precipitation totaled 123 and 101 cm during the years 1970 and 1971. Approximately 70 percent of this fell as snow during the months of November through April. The heaviest precipitation fell in November, December, and January in 1970 and in December, January, and March in 1971. In general, the least amount of precipitation falls in the months of June through August; however, in both 1970 and 1971 the month of February was also dry (2 cm or less).

Summer and fall precipitation data are available for the years 1953 through 1971. In 1950, two permanent climatic stations were established at the Utah State University College Forest. One was located in a spruce stand at the present study site (B station), and the other was established in a partially cut Engelmann spruce stand about 0.8 km southeast of the study site (A station). A third was located in a meadow roughly the same distance to the north of the study site (M station) in 1965. Table 2 presents monthly precipitation and July through September totals for the available period of record at A station. July was the driest summer month on the average (1.9 cm) with June (4.4 cm) being the wettest. The July through September rainfall total varied from a low 1.8 cm in 1956 to a high of 23.6 cm in 1965.

Table 2. Precipitation record of A station at the Utah State University College Forest. Totals are in centimeters of precipitation.[1]

Year	Month of year					July-Sept. total
	June	July	Aug.	Sept.	Oct.	
1953	--	0.9	1.5	0.6	2.7	3.0
54	5.7	1.3	1.3	3.3	3.7	5.9
55	1.6	1.7	2.9	5.5	6.0	10.1
56	1.6	0.9	0.4	0.5	1.5	1.8
57	3.7	1.3	4.0	1.5	4.4	6.8
58	2.5	2.4	3.0	2.2	--	7.6
59	2.2	1.3	10.0	3.8	7.9	15.1
1960	1.7	1.4	0.9	5.5	--	7.8
61	--	3.7	2.0	10.9	3.3	16.6
62	--	5.9	1.7	2.9	2.3	10.5
63	1.7	0.0	1.2	7.0	1.3	8.2
64	10.8	0.6	0.8	4.2	--	5.6
65	3.0	4.7	8.4	10.5	0.9	23.6
66	--	1.2	1.8	2.8	--	5.8
67	--	0.9	0.4	1.1	3.2	2.4
68	--	1.9	13.0	1.6	10.4	16.5
69	15.5	2.4	0.4	1.3	--	4.1
1970	5.0	2.0	0.1	4.8	13.3t	6.9
71	2.9t	1.0	2.7	4.5t	11.2t	8.2
Mean	4.4	1.9	3.0	3.9	5.1	8.8
Years Record	13	19	19	19	14	19

[1]Unpublished data on file with Dr. T. W. Daniel, Forest Science Department, Utah State University.

[t]Precipitation in a standard 8-inch (20.3 cm) rain gage at the immediate study site (Tower station).

Rain at A station was collected in a standard 8-inch rain gage at about 1 meter above the ground.

Air temperature and relative humidity

No complete monthly temperature records are available for the study area or adjacent locale. The lowest air temperature recorded at the study site by an alcohol minimum thermometer for the winters 1969-70 through 1971-72 was -28 C (-18 F) in early January, 1972. Summer

maximum temperatures usually do not exceed 24 C (75 F); the highest recorded air temperature at B station was 27 C (80 F) which occurred in mid-July, 1954. Table 3 presents the mean monthly air temperature record at B station.

Table 3. Mean monthly temperature at B station, Utah State University College Forest.[1] Temperatures are in C.

Year	Month of year				
	June	July	Aug.	Sept.	Oct.
1950	--	--	--	7.2	5.5
51	--	14.2	12.2	8.9	0.8e
52	--	13.6	14.2	11.4	7.5
53	--	16.1	14.2	11.4	4.2
54	7.5	15.5	13.0	8.9	--
55	--	13.3e	14.2	8.3e	--
56	--	13.9	11.9	9.7	--
57	7.5	14.2	13.9	--	--
58	--	13.3	15.0	9.2	5.0e
59	--	15.5	12.8	--	--
1960	--	15.3	11.9	--	--
61	--	--	--	--	--
62	--	11.7e	12.2	--	--
63	--	--	--	--	--
64	--	--	--	--	--
65	--	--	--	--	--
66	--	--	--	--	--
67	--	--	15.8	10.3	--
68	--	14.7	9.4	6.7	--
69	--	14.7	16.1	10.5	--
1970	--	14.7	15.8	5.8	--
71	--	13.9	15.0	5.3e	--
Mean	--	14.4	13.6	8.6	--
Years Record	2	15	17	14	5

[1]Unpublished data on file with Dr. T. W. Daniel, Department of Forest Science, Utah State University.

[e]Some mean daily temperatures in the month were estimated.

Data were obtained from charts of a recording hygrothermograph placed in a standard U. S. Weather Bureau shelter. Daily mean temperatures were averaged over a month to give mean monthly temperature.

Mean relative humidity for the summer months is generally low (30 percent or less) except for short periods of rainy weather when it may rise to 100 percent. Rapidly moving storm systems can cause rapid changes in relative humidity in a 24 hour period (or less).

Wind movement

Wind speeds at the study site are generally less than 8 km per hour (5 miles per hour) because the site is partially protected by local land features and because it is near the topographic divide (source area of valley winds, Geiger, 1966). Table 4 gives mean daily wind movement for the June through October months at the study site.

Table 4. Mean daily wind (kilometers) for the months June through October at the Tower climatic station, Utah State University College Forest.[1]

Year	June	July	Aug.	Sept.	Oct.
1970	--	64.3	53.4	73.1	--
1971	82.5	61.0	45.3	82.7	78.2

[1]As determined by a three-cup, totalizing anemometer placed at 10 meters above the ground (Belfort 5-349 series).

Soils and Geology

The underlying earth materials of the study site belong to the Wasatch Conglomerate. The Wasatch Conglomerate is a formation of the Wasatch Group, a series of earth materials rich in iron oxides and formed during humid Eocene to Paleocene times.

Since its exposure to the elements, the Wasatch Conglomerate has been altered both physically and chemically. Despite some changes, there are still strong evidences of stream action or layering of various materials in the conglomerate, i.e., there are many rounded boulders, layers of sand, gravel, and clay. Investigation of the conglomerate near the study area suggests some possible periglacial activity (Dr. A. R. Southard, personal communication, 1972). Some mass slippage of earth materials, accumulation of rounded rock debris and permafrost soil markings are evidence of this. Exposure of the soil to weathering and biological activity has leached the surface horizons of fine soil materials, enriched the surface with organic matter, and deposited clay at the deeper depths with enough concentration to constitute an argillic horizon.

The soil at the study site has been tentatively classified as belonging to the fine, loamy, mixed family of cryic paleboralfs (Dr. A. R. Southard, personal communication, 1972). Some selected physical and chemical properties of the soil at the study site are given in Table 5. The rock content at the study site is approximately 30 percent for the first 60 cm of soil and is nearly 0 percent from 60 cm to over 2 meters. In contrast, soil pits less than 1 km from the immediate study site have rock contents of 50 percent or greater throughout the soil horizons (Eaton, 1971, and personal observations).

Table 5. Some selected physical and chemical properties of the College Forest soil type.[1]

Depth increment (cm)	pH	CEC me/100g	Percent organic matter	Mechanical analysis				
				% sand	% silt	% clay	Texture	Bulk density
0 - 10	6.2	18.2	6.3	51	36	13	loam	1.03
10 - 25	5.4	8.8	1.4	51	34	15	loam	1.03
25 - 38	5.5	7.4	0.8	48	36	16	loam	1.48
38 - 53	5.9	14.6	0.5	43	32	25	loam	1.48
53 - 71	5.4	12.0	0.3	34	40	26	loam	1.69
71 - 89	5.3	20.3	0.4	20	38	42	clay	1.85
89 - 117	5.4	21.2	0.1	22	39	39	clay-loam	1.79
117 - 142	5.3	21.6	0.2	30	33	37	clay-loam	1.76
142 - 188	5.5	17.2	0.3	33	34	33	clay-loam	1.81
239 - 259	5.4	12.6	0.3					

[1]Samples were collected from a soil pit in a conifer stand at the immediate study site by Dr. A. R. Southard of the Soils and Biometeorology Department at Utah State University. Analyses were done by the Agriculture Experiment Station soils laboratory.

METHODOLOGY

This study was conducted in cooperation with a continuing research project by the Watershed Science Unit of Utah State University. Assistance in field work, procurement of needed equipment, and cooperation in providing basic climatic data helped greatly in conducting the study.

Data for this study were collected in two field seasons. Exploratory work was done in the summer of 1970 to assess the usefulness of thermocouple psychrometers in field applications, and to determine rooting patterns in the Engelmann spruce type, variability of soil water potential, rainfall, and other parameters. During the summer of 1971 data were collected in accordance with the objectives of the study and findings of the first summer's work. Later sections treat the two phases of the study separately.

One assumption made in the proposal stage of the study was that a fixed effects model would be used in all statistical tests and data interpretations. No attempt is made to extrapolate results to the entire College Forest or to the Engelmann spruce-subalpine fir type as a whole. It is conceivable, however, that results from this study may apply in principle to other regions having similar topography, soils, and stand development.

First year

Field work was performed during the period of June through September, 1970. At this time one experimental plot was located in a spruce stand and one was located in a nearby meadow area. In Figure 3

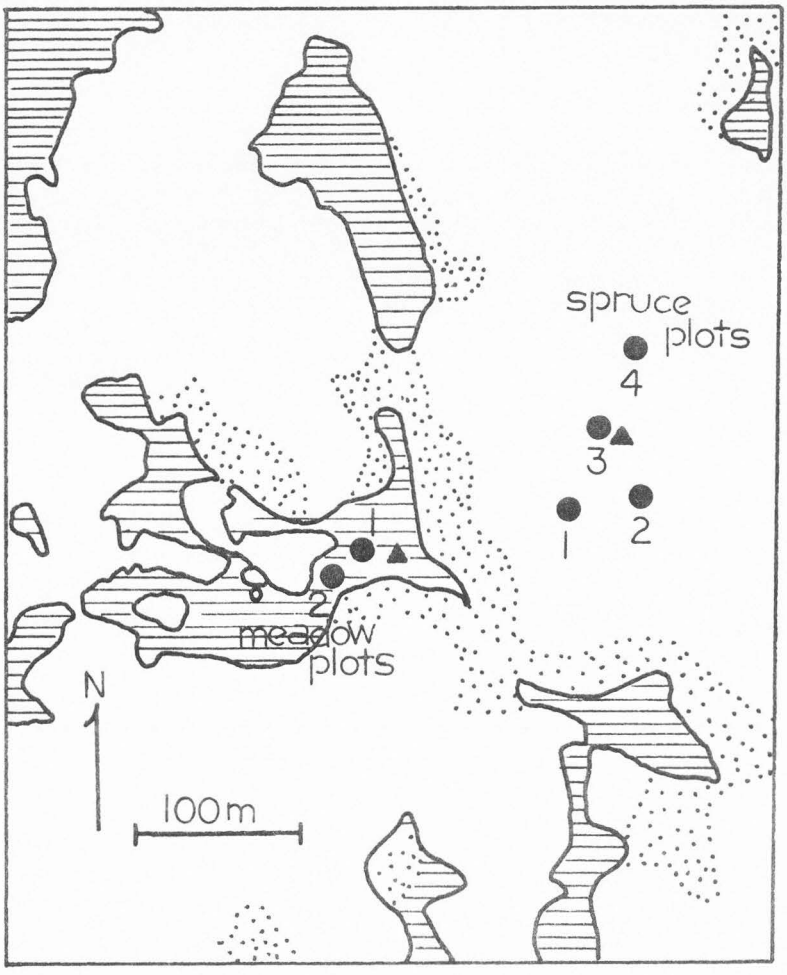

Figure 3. Map of the study area showing vegetation types and plot locations.

these are designated as spruce plot 1 and meadow plot 1. It was felt that any investigation of water relations should include a study of both meadow and conifer environments, as a mosaic pattern of spruce and meadow is common to the Engelmann spruce type. Both plots were approximately ten by ten meters in size and were fenced to exclude grazing by sheep. A one meter square grid of string was laid over the plot surfaces and instrumentation was located by randomly selecting from these sampling areas. Twenty-eight neutron probe access tubes were installed at meadow plot 1 while twenty-five were installed at spruce plot 1. At both plots, three stacks of soil psychrometers at 15, 30, 45, and 90 cm depths, and three #10 can rain gages were randomly located. The depth of placement of soil psychrometers was chosen to conform with findings of a root distribution study done early in the season where the bulk of the root system of Engelmann spruce was found in the first 90 cm of soil.

Second year

Following the first data collection period, data were analyzed and plans made for the second summer's work. In early June, 1971, three additional plots were located in the Engelmann spruce stand and one additional plot in the meadow area. Figure 3 shows the location of all the plots studied from June, 1971 to late October, 1971. The criterion for selection of the new spruce plots was availability of mature Engelmann spruce dominants. Spruce plot 1 met this qualification and was also studied the second year.

At each of the four spruce plots, three sound, mature, and rot-free Engelmann spruce trees were chosen for instrumentation with

thermocouple psychrometers. A reduction in variability from tree to tree was expected by stratifying the sample of trees at each plot in this manner.

Soil instrumentation were placed roughly in the center of an area encompassed by the three psychrometer-instrumented trees. By this procedure, the soil parameters measured at this location would probably be correlated with internal tree water potential. At each of the four spruce plots, the following soil instrumentation was installed:

1. a neutron probe access tube reaching 90 cm in depth,
2. a stack of soil psychrometers (one at 15, 30, 45, and 90 cm depth),
3. a stack of tensiometers (one at 15, 30, 45, and 90 cm depth), and
4. two stacks of soil temperature thermocouples at the same depths as (2) and (3).

All soil instruments were located within one meter of an access tube. At the meadow plots, soil instrumentation was the same as at the spruce plots with the exception that soil psychrometers were installed at the 5 cm depth but not at the 45 and 90 cm depths. Data from the previous summer showed the soil to be too wet at depths greater than 45 cm to be within the range of thermocouple psychrometers.

In order to determine any differences in soil water content between plots, additional neutron probe access tubes were installed in meadow plot 2 and all of the spruce plots. They were placed randomly within the confines of meadow plot 2 and distributed evenly as possible around the centers of the spruce plots within the root zone of psychrometer-instrumented trees.

A view of the soil instrumentation can be seen in Figures 4 and 5. For an overhead view of instruments and tree locations at the spruce plots, see Figures 24, 25, 26, and 27 of Appendix C.

Basic atmospheric variables were measured continuously starting in June and ending in mid-October, 1971. Global radiation was to have been measured with a Starr radiometer and recorded on a potentiometric recorder, but mechanical difficulties prevented use of such a system. As a substitute, two bimetallic actinographs (one as a backup) were used to obtain an estimate of global radiation. Air temperature and relative humidity were estimated by a hygrothermograph placed in standard Weather Bureau shelters at both Tower and B stations. Air temperature was checked periodically with a set of maximum-minimum thermometers at each of the instrument shelters and humidity was checked against an aspirated Assman psychrometer. Wind movement was estimated by a three-cup totalizing anemometer at Tower station at about ten meters above the ground (Figure 6). Rainfall was estimated with a recording, weighing-type eight inch (20.3 cm) rain gage at Tower station and throughfall (rain falling through or dripping from the canopy) with an east-west transect of seven #10 cans at spruce plots 1, 2, 3, and 4.

Intermittent measurements of other variables for the study were collected according to the schedule in Table 6. Within-season measurements are defined as those taken at regular three to four day periods within the summer and early fall months. Diurnal measurements are those taken at about one-hour intervals to determine the daily, cyclic response of the variable in question. The schedule presented in Table 6 was followed as closely as possible with only a few departures because of inclement weather and instrumentation difficulties.

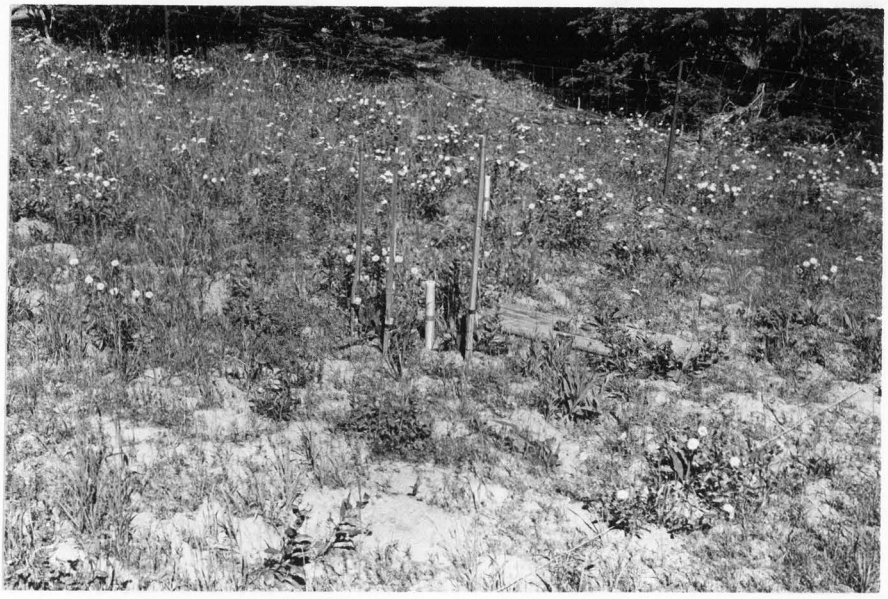

Figure 4. Basic instrumentation network placed at all plots. This photograph was taken at meadow plot 2 and shows the placement of tensiometers, access tube and soil psychrometers (lead wires are under a can in the right-center portion of the photograph).

Figure 5. Instrumentation at spruce plot 2.

Figure 6. Tower climatic station located at the Utah State University College Forest.

A further note should be made of the diurnal measurements. The time interval between the seven selected days varied from one to four

Table 6. Schedule of measurements of non-atmospheric variables taken at the study site.

Location	Time (MST)	Instruments
	Within-season	
meadow plots	0900 - 1000	soil psychrometers, suction tensiometers, soil temperature thermocouples
spruce plots	1000 - 1130	tree psychrometers, suction tensiometers, soil temperature thermocouples
	1130 - 1200	pressure chamber
	Diurnal	
spruce plots	0600 - 2200 at approximately one-hour intervals	tree psychrometers, pressure chamber, soil psychrometers

weeks to assure collecting data for a wide range of meteorological conditions. Measurements were taken at two of the four spruce plots because six tree psychrometers and associated soil measurements were the maximum that could be handled with one person and manual read-out equipment. Choice of plots was alternated from plots 1 and 2 to 3 and 4.

Collection of data for the secondary objective, the effect of rain on soil water potential, consisted of taking soil psychrometric measurements and measuring throughfall of rain when a rainstorm occurred.

Analyses of variance of internal water potential data (stem and trunk water potential) were performed by use of a completely randomized design with within-season variations in water potential as treatments, and plots as replications within treatments. Sampling error of psychrometrically determined water potential was determined because data values could be assigned to the individual experimental units--the trees themselves. Variation among pressure chamber determinations was small, and since the data values could not be assigned to individual trees, but only to plots as a whole, no sampling error was determined. A randomized block design by which variation due to plots could be subdivided was not used in analysis of the data as examination of differences in soil parameters between the four plots showed no differences which could justify blocking.

The purpose of analyzing the variation of water potential data was to determine whether or not changes of water potential in time were significant. As stated earlier, it was hypothesized that such changes should occur--if they had not, any further analysis of the data would have been precluded, i.e., there would not have been any reason to attempt to relate internal water potential to environmental factors.

Construction, Calibration and Operation of Instrumentation

Construction

Twenty-four manometer type tensiometers were used in the study. Some were built commercially while others were manually constructed. The principle of all the instruments was the same: changes in matric potential were measured by displacement of a mercury column which was connected to a continuous water column extending from the mercury pool

through the capillary tube and instrument body to a ceramic cup at the soil end. Water was then free to move through the ceramic cup into the soil in response to a matric potential gradient; the assumption was made that porosity in the ceramic element presented no serious resistance to flow, i.e., it would cause no lag in pressure equilibrium. Preparation of these involved checking seals between glass and rubber for leaks, replacing broken capillary tubes, cleaning the metallic millibar scales and painting the metal surfaces to retard rust.

Spanner-type thermocouple psychrometers with a 200-mesh screen rather than a porous ceramic chamber were constructed for soil and trunk water potential measurements. Figure 7 shows the design materials and dimensions of these psychrometers. For detailed construction steps of these thermocouple psychrometers and listing of specifications and manufacturers the reader is referred to Brown (1970) and Wiebe, et al. (1971).

Soil temperature thermocouples were constructed in nearly the same fashion as the ambient temperature thermocouples placed in the psychrometers. About one centimeter of insulation was removed; the copper and constantan wires were twisted and soldered together with silver solder; the junction was cleaned in acetone and water, then dried, and finally encased in a thin jacket of RTV silicone rubber to prevent chemical deterioration.

Calibration

Before transporting the tensiometers to the field, they were filled with mercury and water, mounted on a work bench in the upright position, and freed of any air bubbles in their systems. A stream of air was

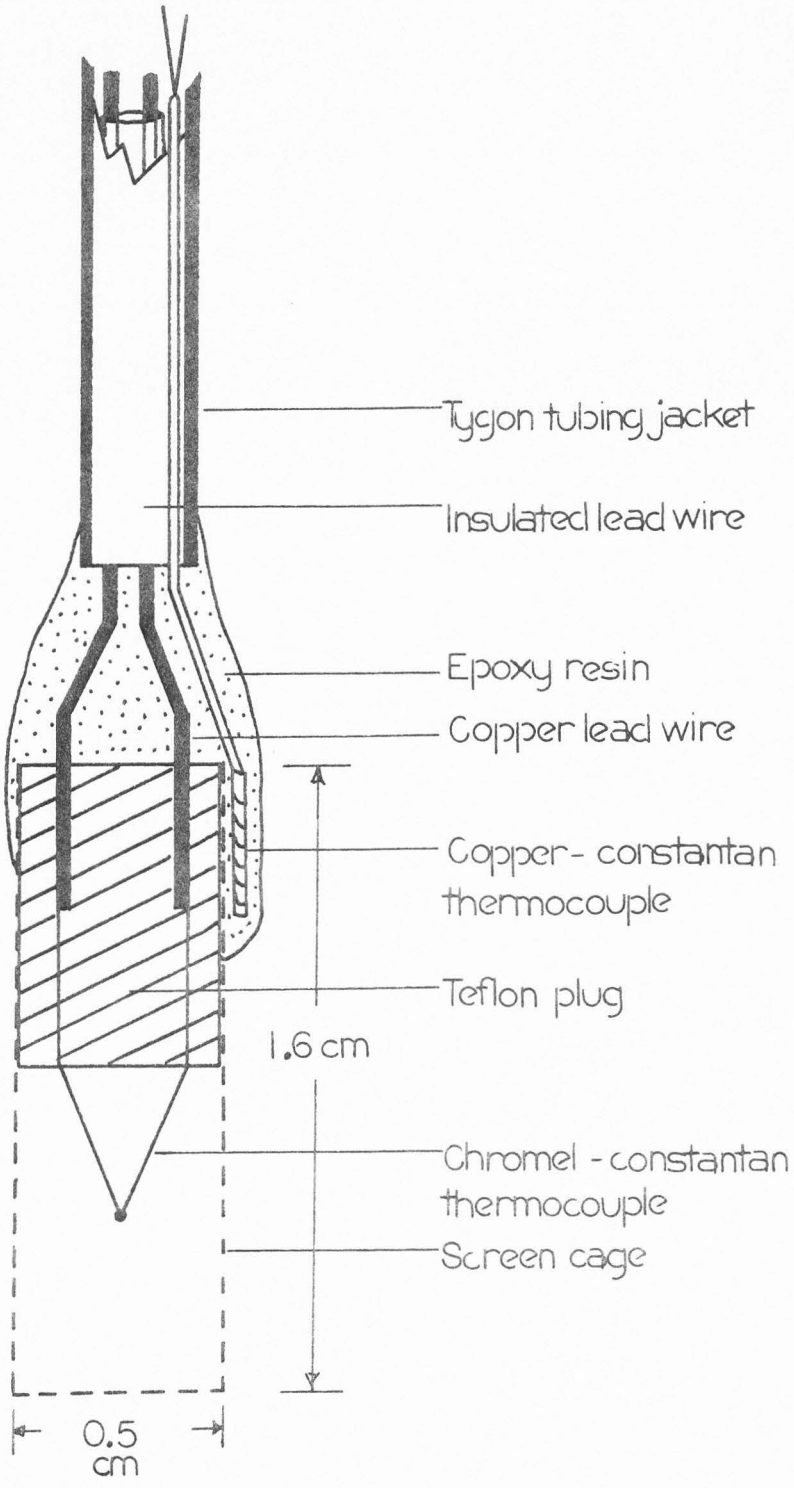

Figure 7. Mean longitudinal section showing construction details of a screen type thermocouple psychrometer (After Meyn and White, 1972).

The Keithly unit was equipped with a 4.5 ma cooling circuit and an electrical 0 C reference junction. The electrical junction, however, was not used and an ice-water reference circuit was devised. For physical protection and shielding against temperature fluctuations, the entire unit was placed in an open-faced plywood box provided with about 2 cm of styrofoam insulation on the inside surfaces.

The thermocouple psychrometers were prepared for calibration as follows: Kimax test tubes (13 by 100 mm) were lined with filter paper to within 1 cm of the open end. Six to eight drops of calibration solution were added to the tubes with an eye dropper. Each thermocouple psychrometer, fitted with an "00" stopper at the tygon jacket end, was then firmly, but not tightly, inserted into a test tube. Because the stoppers were not tightly in place, it was necessary to seal the junction between the test tube and rubber stopper with RTV silicone sealant.

While the psychrometer calibration assemblies were sitting and the water seals were drying, the water bath was filled with water and the water was heated to obtain the desired temperature. After a stable temperature had been reached, the psychrometer calibration assemblies were lowered into the bath. Ten psychrometers could be placed in the bath at one time. The lead wires of the psychrometers, except for the last 30 cm, were bound together and fastened so that they were completely covered with bath water. The styrofoam cover of the water bath was positioned with the lead ends of the psychrometers exposed to the room environment. Water in the bath was allowed to circulate two hours so that a stable temperature in the system and no temperature gradients between outside and inside the calibration tubes were assured. After this period the psychrometers were ready to be read.

Figure 8 shows a schematic of the circuitry used in calibration and in the field. The soil psychrometer and soil temperature units are shown separately for clarity while in reality they are together as one unit (see Figure 7) in either the calibration tube or in the tree or soil. The actual calibration procedure for each of three runs per solution and temperature was as follows:

1. Copper leads of each psychrometer were connected to the voltmeter (Figure 8) and the needle was zeroed with the microvoltmeter in the "on position."

2. The cooling switch was depressed for a specified time.

    a. 10 seconds for 0.1 molality
    b. 15 seconds for 0.3 molality
    c. 15 seconds for 0.5 molality
    d. 30 seconds for 1.0 molality

3. Upon release of the cooling switch, the maximum emf, after the initial spike in some cases, was recorded.

The bath water was allowed to circulate 15 minutes between runs. Three measurements per solution and temperature allowed for detection of leaking tubes (rapidly falling readings) and for a more reliable measure of the true emf.

Sixteen of forty psychrometers constructed for the study were calibrated at 8, 14, 20, and 26 C over solutions of 0.1, 0.3, 0.5, and 1.0 molal NaCl. Such a range of temperature and osmotic potential was the maximum expected in the field (based on work the summer of 1970). Psychrometric output (μv) versus ambient temperature scatter diagrams were plotted for all four NaCl solutions. In each diagram the scatter of points at each temperature was considerable suggesting that, even with uniformly constructed units, a range of emf responses can be expected. Since developing a predictive equation for each psychrometer at the complete range of osmotic potentials and temperatures was impractical,

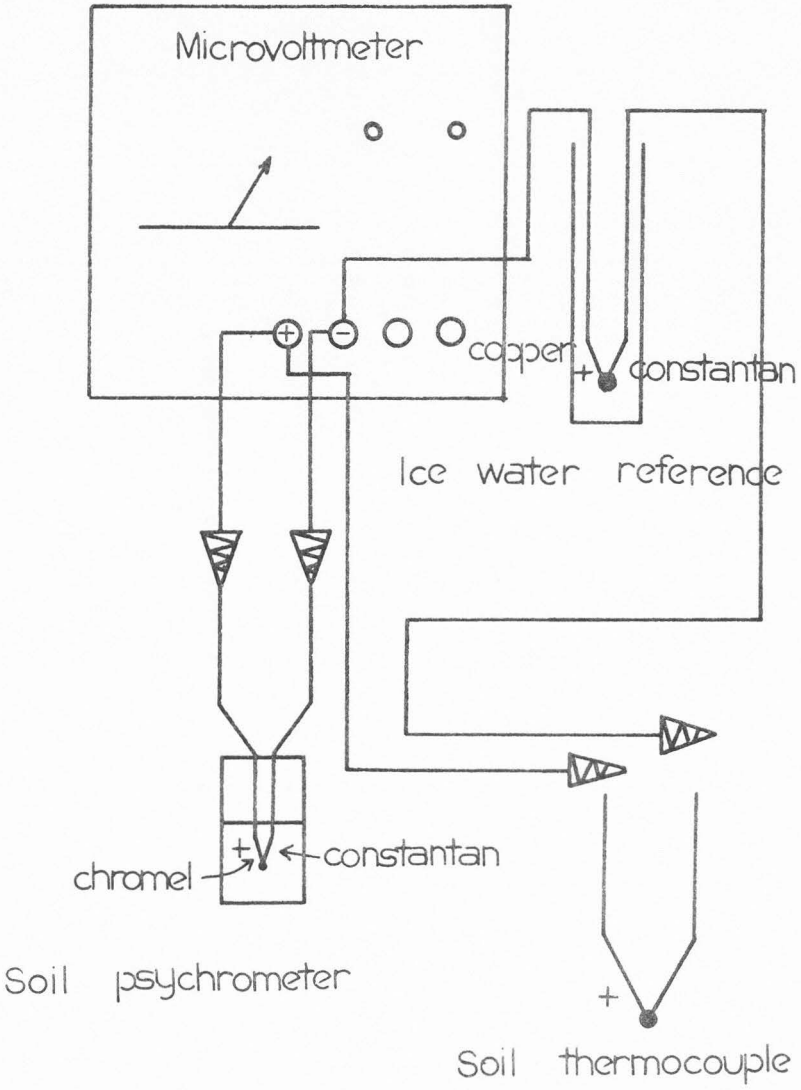

Figure 8. Schematic drawing of circuitry used for measuring psychrometric emf (after Meyn and White, 1972).

a logical alternative was to group psychrometers having similar response characteristics and to develop a limited number of predictive equations. The method adapted in this study was to divide regression scatter of the 16 fully-calibrated units into three regression bands. The scatter of emf's for temperatures between 8 and 26 C over the 0.5 molal salt solution was chosen as the graphical guide for determining which of three regressions a given psychrometer would match. This scatter of points (Figure 9) was divided into three bands by placing evenly-spaced parallel lines through the data points. The regression band showing the greatest emf for a given temperature was called regression #1, the band with lesser response, regression #2, and the band with least response, regression #3. Calibration of the remaining 24 psychrometers was completed at a range of temperatures from 8 to 26 C, but only over a 0.5 molal salt solution. Finally, linear regression lines were plotted for all 40 psychrometers at 8, 14, 20, and 26 C and a NaCl solution of 0.5 molality. These were graphically superimposed over the regression bands as illustrated in Figure 9 and each psychrometer was rated as regression #1, #2, or #3. Most of the units matched the regression #1 band, while few fit the regression #3 band. The objective of the above procedure was to reduce total calibration time, but at the same time not sacrifice much reliability of the resulting predictive equations. The end result was three sets of calibration data with each having roughly one-third the variability of all the data considered as a whole.

A mathematical model of eight independent variables was proposed to predict water potential as a function of psychrometric emf and

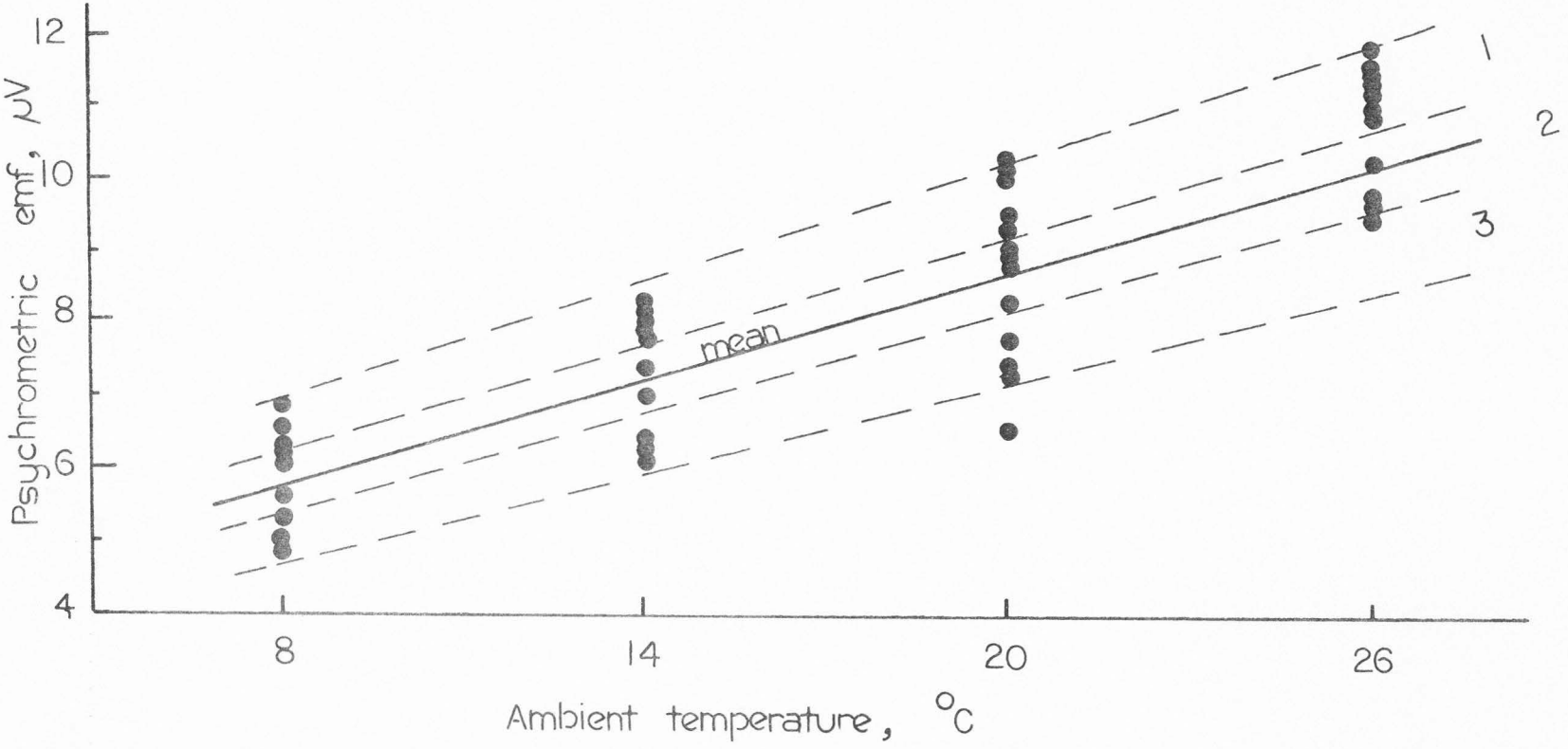

Figure 9. Determination of thermocouple psychrometer calibration regressions by measuring psychrometric emf versus temperature over a 0.5 molal NaCl solution.

ambient temperature. The selection of variables was based on earlier laboratory work (Meyn and White, 1972). The proposed model was:

$$y = a + bX_1 + cX_2 + dX_1^2 + eX_2^2 + fX_1X_2 + gX_1X_2^2 + hX_2X_1^2 + iX_2^2X_1^2 \quad (2)$$

where:

y = water potential, - bars,
X_1 = psychrometric emf, microvolts,
X_2 = ambient temperature, C,

and X_1^2, X_2^2, X_1X_2, $X_1X_2^2$, $X_2X_1^2$, and $X_2^2X_1^2$ are transformations which describe warpage of the three-dimensional relation between water potential, ambient temperature, and psychrometric emf.

The best fit of the proposed model was determined by multiple regression analysis for each of the three sets of calibration data (regressions #'s 1, 2, and 3). Predictive equations were obtained from these analyses by selecting those variables which were statistically significant at the $\alpha = 0.01$ level. The complete regression analyses are tabulated in Tables 20, 21, and 22 of Appendix D. All psychrometric data collected during the study were reduced to predicted water potential by these equations. Regression #2 was assumed for all units used during the first summer of work. Table 7 summarizes the three predictive equations along with an estimation of error in predicting water potential at the mean ambient temperature and emf of the calibration data.

Table 7. Water potential predictive equations for thermocouple psychrometers based on laboratory calibration data.

Regression	Equation[a]	Confidence intervals at the 95 percent probability level[b]
1	$y = -2.1643 - 1.7356\ X_1 - 0.1884\ X_1^2 + 0.0068\ X_2X_1^2$	-20.6 ± -0.4 bar
2	$y = -1.7389 - 2.188\ X_1 - 0.1651\ X_1^2 + 0.0067\ X_2X_1^2$	-21.3 ± -0.4 bar
3	$y = 0.2856 - 4.668\ X_1 + 0.0833\ X_1X_2$	-21.7 ± -0.8 bar

[a] y = predicted water potential (- bars),
X_1 = psychrometric emf in microvolts, and
X_2 = ambient temperature in C.

[b] predicted water potential at a mean temperature of 17 C and psychrometric emf of 7.9 microvolts.

As in any regression problem error in prediction of the dependent variable increases at either limit of the regression. Confidence limits at the 95 percent level were calculated for outer limits of psychrometer regression #1. They are presented as follows:

X_1 = 1 microvolt
X_2 = 5 C $\qquad y_{(1)} = -3.8 \pm -0.8$ bar

X_1 = 20 microvolts
X_2 = 25 C $\qquad y_{(1)} = -42.1 \pm 3.7$ bars

These calculations approximate the maximum limits of error in estimating water potential with thermocouple psychrometers assuming there are no errors in measurement of the independent variables.

Installation and operation

Thermocouple psychrometers were installed in the north side of tree trunks of selected spruce trees. At about one meter from the ground loose bark was removed and a hole was drilled to a depth of approximately 1.5 cm by a 0.5 cm diameter drill bit. The actual depth of each hole varied according to thickness of inner bark, but an attempt was made to drill a hole deep enough so that one-half of the sensing chamber was in xylem and one-half was in phloem. After inserting the psychrometer assemblies, the void around the entry point and the immediate area was sealed with modelling clay. A layer of RTV silicone rubber was applied thinly over the clay and heavily around the psychrometer leads at the point where they emerged from the trunk, thus providing good physical support. All of the above measures were taken to assure that there was no gaseous exchange between the atmosphere and psychrometer chamber. After the RTV had cured, a cardboard mold of the dimensions 20 by 20 by 10 cm was tacked to the trunk surface with the lead wires positioned so that they extended through the center of the outer mold wall. Polyurethane foam was poured into the molds and allowed to set. This foam, when dried, provided effective insulation against rapidly changing bark temperatures.

Soil psychrometers were installed by first excavating a hole 90 cm deep. A short length of copper tubing about 0.5 cm in diameter was inserted into the side of the hole at selected depths and 15 cm long cores of soil were removed. Thermocouple psychrometers were carefully inserted until the end of the chambers reached the back end of the holes. The gap between the psychrometer leads and the soil was

back-filled with soil as much as was possible and, when all psychrometers were installed at a given site, the hole was refilled with the original soil.

Soil temperature thermocouples and tensiometers were installed in a similar fashion. A hole was excavated to the desired depth, a slurry of mud and water was poured into the hole, and the thermocouple or tensiometer was inserted. A slurry assured full contact with the surrounding soil surface. Before installing tensiometers, they were zeroed as outlined previously.

Thermocouple psychrometer outputs were measured with a microvoltmeter and temperature reference circuitry as schematically shown in Figure 8. The procedure for taking measurements was the same as in calibration of these instruments except that only one emf measurement of a given psychrometer was taken at any given time. Ambient temperatures of the psychrometers were also taken concurrently. Some trial and error setting of the voltage scale was necessary because of uncertainty as to the range of water potential being measured. A photograph of the portable voltmeter and ice-water reference unit as it was used in the field is shown in Figure 10.

Water potential determinations were made on small stems of Engelmann spruce and subalpine fir at one to two meters height in the vicinity of each plot (by use of a semi-portable nitrogen cylinder and pressure chamber). Five branches about 12 cm long were collected from the lower branches of trees at each spruce plot, and two centimeters of bark were removed from the cut ends. Each branch was individually placed in the chamber and pressure was slowly applied until water

Figure 10. Microvoltmeter, switching box, and ice-water reference used to measure water potential by thermocouple psychrometers.

appeared on the cut end. All pressure chamber measurements were taken within five minutes or less of the time the stems were removed from the tree.

Throughfall of precipitation was measured by pouring the contents of each can into a 1000 ml graduated cylinder. Samples were collected immediately after dripping from the forest canopy ceased in order to minimize evaporative losses.

RESULTS AND DISCUSSION

The first part of this section will present analyses of variance of experimental data. Following this, correlations between internal water potential and environmental factors will be presented--first graphically, and then in mathematical form as determined by multiple variable regression analyses. The third part of the section will show relations found between summer precipitation and the soil drying cycle and discuss possible implications of these relations with respect to the soil-plant-atmosphere system. Throughout the section comparisons of the results with other studies will be included whenever possible.

Water potential terminology follows that most commonly used in the literature with the exception of the following. To distinguish between water potential measurements made by the pressure chamber and those obtained from thermocouple psychrometers, the following terms are defined. Trunk water potential is denoted as ψ_T and is a psychrometric measurement of water potential while stem water potential is denoted as ψ_S and represents water potential of a tree obtained by placing cut twigs in the pressure chamber.

Variability of Water Potential Measurements

Throughout the summer of 1971 psychrometric measurements of water potential were more variable than pressure chamber measurements. A tabulation of all diurnal and selected within-season water potential measurements can be found in Tables 17 and 18 of Appendix B. Variability of psychrometrically-determined water potentials was higher during

periods of low water potential (maximum internal water deficit) than during periods of high water potential (minimum internal water deficit). Variability among pressure chamber measurements was lower than estimations by thermocouple psychrometers and less dependent upon the magnitude of internal water deficits.

Analysis of variance of ψ_T

Psychrometric data collected at periodic intervals during the summer of 1971 were converted to water potential by the predictive equations previously presented in Table 7. An analysis of variance of trunk water potential in 12 spruce trees was calculated for the times of measurement in which at least three of four plots were measured. Serial correlation between times of measurement entered into the analysis were assumed to be negligible. Examination of within-season variation of ψ_T showed clearly that ψ_T one day was not highly dependent on ψ_T four days to a week earlier (corresponding to the period of time between successive measurements). Evidence for this was the rapidly changing nature of ψ_T with changes in the weather; and, changes in the weather, of course, did not occur with regularity. Analysis of variance of ψ_T measurements is given in Table 8. Within-season variations of ψ_T were significant at the $\alpha = 0.05$ level. A great amount of variability among plots (experimental error) and among subsamples (the trees themselves) was found.

Explanation of large experimental error in psychrometric determinations of ψ_T may include the following elements, i.e., those sources of variation not subdivided in the analysis but which are included in experimental error. With knowledge of the Seebeck principle in

operation of thermocouple psychrometers, one might expect the largest single source of error to be the effect of temporary temperature gradients between reference and measuring junctions which are caused by heat being conducted along the lead wires. All implanted thermocouple psychrometers were well insulated with foam as previously described and

Table 8. Analysis of variance of trunk psychrometer readings made at various times throughout the summer months of 1971 at 1000 to 1130 hours.

Source of variation	Degrees[1] freedom	Sum of squares	Mean square	F-ratio
Mean	1	16,827		
Treatments[a]	15	6,940	462.7	2.11*
Plots[b]	48	10,513	219.0	
Trees[c]	111	16,007	144.2	
Total	175	50,287		

*Significant at 5 percent level.
[1]17 degrees of freedom lost in trees and total because of missing data (psychrometer failure).
[a]Separate, independent measurements of the effect of the environment on trunk water potential as reflected by psychrometric readings.
[b]Experimental units within treatments or experimental error.
[c]Samples within experimental units or sampling error.

the majority were completely shaded from sunlight throughout the day. Careful zero adjustment of each psychrometer prior to reading provided a "bucking voltage" which eliminated any emf between reference and measurement junctions. If an error in psychrometric readings was due to temperature gradients, one would expect readings to be high if air

temperature exceeded the psychrometer temperature and low if air temperature was less than psychrometer temperature. A plot of the difference between air and psychrometer temperatures versus ψ_T for all diurnal measurements of trunk water potential (Figure 11) showed no consistent pattern or relation, hence temperature gradients of this form do not appear to be an important source of experimental error.

Other possible sources of experimental error may have been unavoidable variation in depth of psychrometer implacement, tree to tree differences in transpiration rate, instrument error, and human error--those errors made in operating the voltmeter and cooling circuitry. Tree to tree differences, perhaps, should be given emphasis as surely different crown forms and exposures to wind and radiation have a marked effect on transpiration rate, and transpiration rate in turn directly affects trunk water potential.

The prime source of missing data was due to fouling of psychrometer junctions with resin; inclement weather and instrumentation problems contributed also.

Analysis of variance of ψ_S

An analysis of variance of stem water potential (as measured by the pressure chamber) is given in Table 9. Variation due to subsamples, pressure chamber determinations from an individual tree, was not included in the analysis because such samples were not systematically obtained from a selected set of trees; but rather, they were obtained at random from branches that could be reached in the vicinity of each plot. For samples taken from a given individual Engelmann spruce tree, Kaufman (1968) found a maximum range in pressure chamber determinations of 1.3

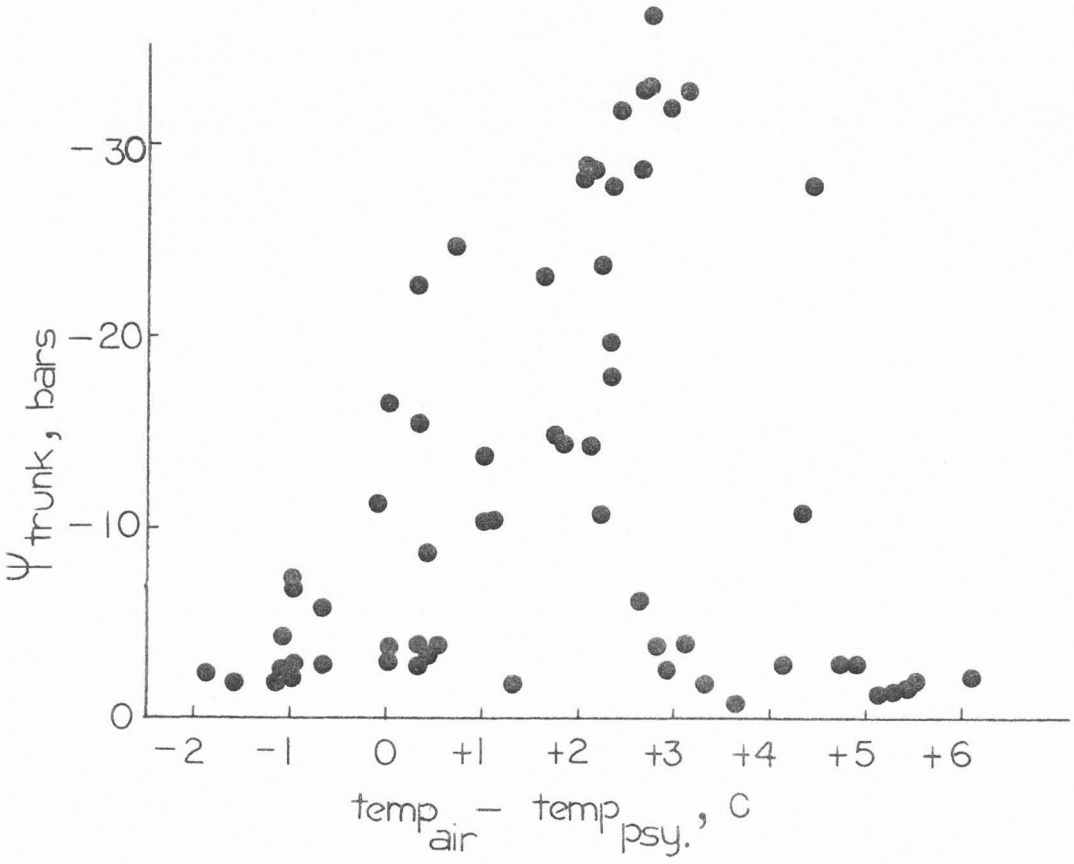

Figure 11. Plot of the relation between trunk water potential and temperature gradients which existed between the air and psychrometer reference junctions at various times of measurement.

bars. Maximum range of 20 samples at the Utah State University College Forest was two bars or less. A small experimental error (Table 9) is

Table 9. Analysis of variance of pressure chamber readings made at various times throughout the summer months of 1971 at 1000 to 1130 hours.

Source of variation	Degrees[1] freedom	Sum of squares	Mean square	F-ratio
Mean	1	14,346		
Treatments[a]	13	419	32.2	23.0**
Plots[b]	30	43	1.4	
Total	44	14,808		

**Significant at 1 percent level.
[1]12 degrees of freedom subtracted from total and plots because of missing data.
[a]Separate, independent measurements of the effect of the environment on stem water potential as reflected by pressure chamber readings.
[b]Plots within treatments or experimental error.

explained by small differences in plot means for the 14 measurement periods (see Table 18, Appendix B). Most of the stem samples were taken from easily reached branches--branches from understory trees and low, drooping limbs from dominant, overstory trees. All of these branches were shaded from radiation. Because Waring and Cleary (1967) claimed a - 7 bars difference could exist between fully shaded and fully exposed samples, stems were never taken from branches which were exposed to sunlight at sampling time. All of the above factors, plus an attempt to procure uniform-sized samples, appear to have greatly reduced experimental error.

Relations Between Water Potential and Environmental Factors

Diurnal fluctuations in water potential

Diurnal fluctuations of trunk water potential (ψ_T) and stem water potential (ψ_S) are presented graphically in Figure 12 and in tabular form in Table 17 of Appendix B. Of the seven days of measurement, four days show a marked diurnal cycle while two days show little change and one day shows a cycle halfway between the extremes. Three variables most closely related to diurnal cycles of ψ_T were wind speed, global radiation, and vapor pressure deficit. Soil water potential and soil temperature were not correlated with ψ_T as they did not vary appreciably during any particular 24 hour period. One can see in Figure 12 that the daily peaks in wind movement corresponded roughly with ψ_T minima, peak radiation input occurred roughly two hours before ψ_T minima and maximum vapor deficit corresponded closely with ψ_T minima. In fact, by inverting the daily graphs of vapor pressure deficit, one can see a close relation with ψ_T throughout each day.

Of the seven days of data, August 10 was the day of maximum internal water stress while July 19 and September 8 were days of minimum water stress (high water potential). The following weather summaries may provide an explanation for the observed fluctuations of ψ_T and environmental factors.

A. July 11. Weather was clear with air temperature, relative humidity, and wind average for the month. The diurnal cycle of global radiation and vapor pressure deficit was smooth with no irregularities.

B. July 19. Overcast conditions, intermittent rain, and cool air temperatures were experienced this day. Weather the day before was similar. An overcast sky and humid weather condition are easily seen in diurnal cycles of radiation and vapor pressure deficit.

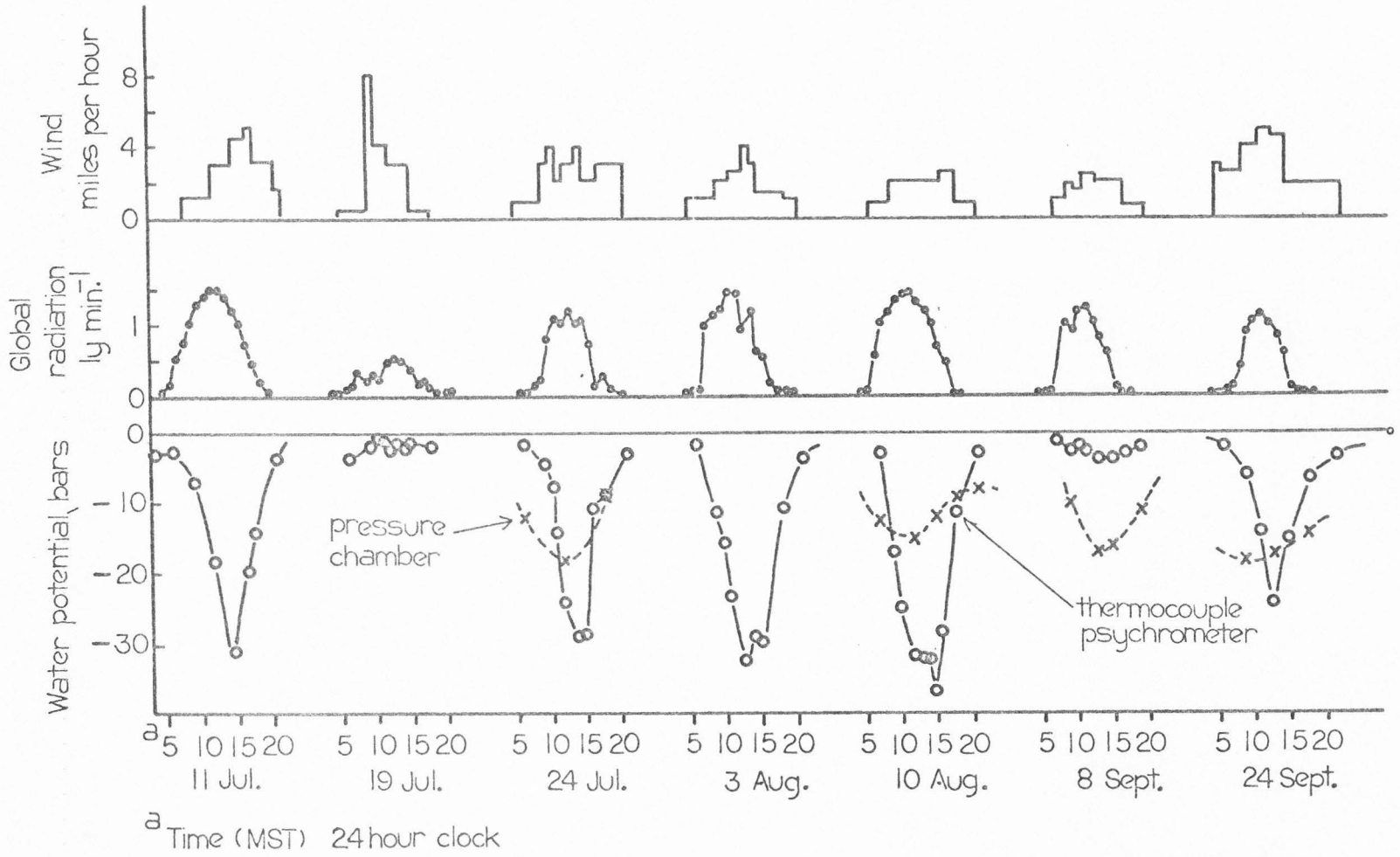

Figure 12. Diurnal variation of trunk and stem water potential in relation to some selected independent, environmental variables.

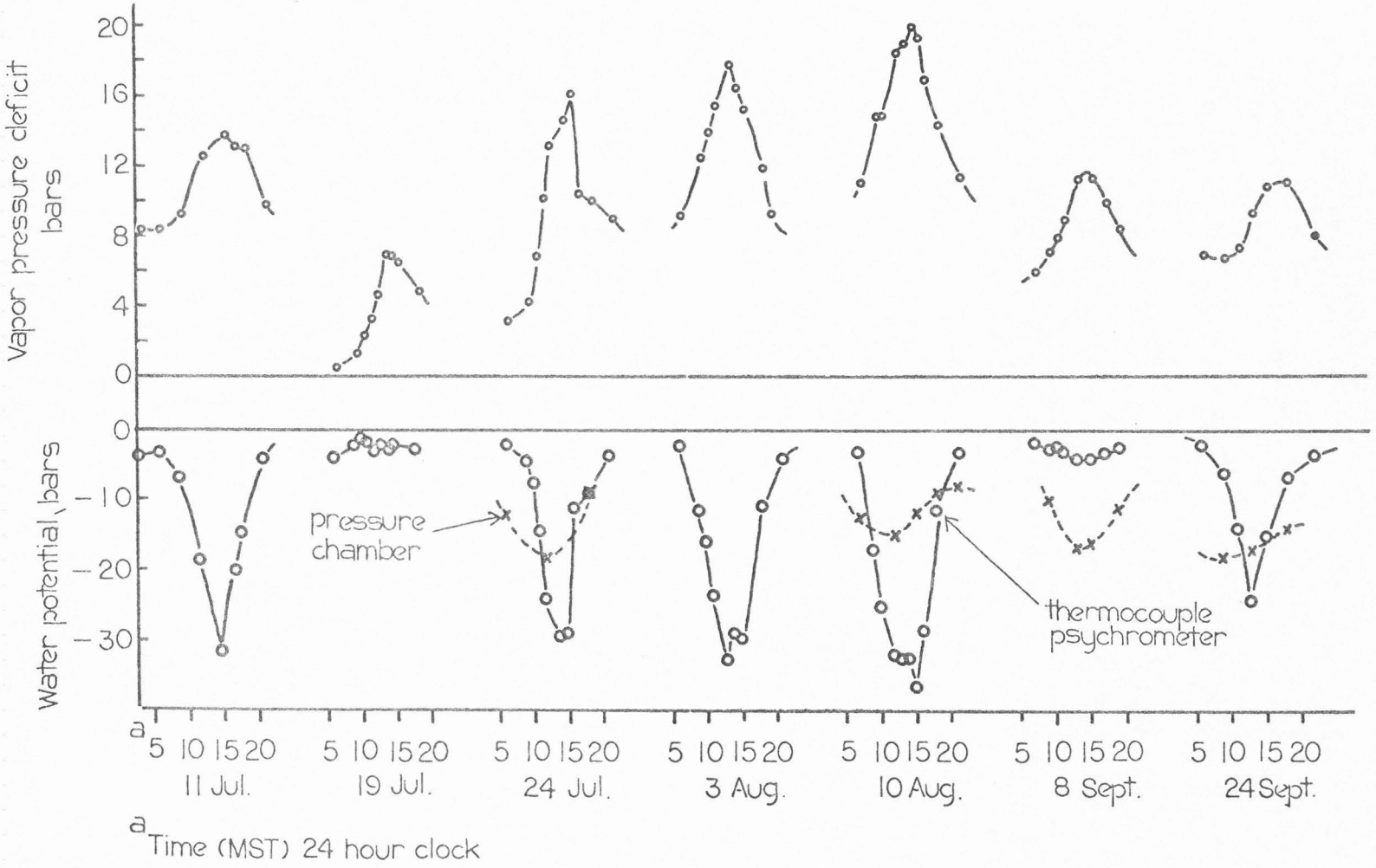

Figure 12. Continued.

C. July 24. Weather this day was highly variable, and as a result, one finds an irregular pattern of ψ_T. The sky was overcast until 0900, then partly cloudy to 1500, with a thunderstorm and full overcast conditions commencing at 1530. At 1700 the sky cleared once again and a temporary increase in radiation occurred. As shown in Figure 12, the rapidly changing atmospheric conditions are seen in the diurnal vapor pressure deficit cycle and corresponding pattern in ψ_T.

D. Aug. 3. Weather this day was similar to July 11, except for a cloudy trend in the afternoon. At this time, the study area was experiencing a weak high pressure system with a warming trend.

E. Aug. 10. This day was chosen for study because weather forecasts called for clear sky and high air temperatures. Weather this day was as predicted. Vapor pressure deficit followed the usual hourly pattern but reached the greatest deficit of the seven days of study. Correspondingly, ψ_T also reached low potentials.

F. Sept. 8. This day was cloudless and cool following a cold, rainy period of several days. Radiation input was nearly as great as possible for that time of year. Vapor pressure deficit was low because of high humidities and low air temperatures. Only a small cyclic decrease in ψ_T was noted.

G. Sept. 24. Weather this day was improving following an extended cold period. Skies were cloudless as indicated by the radiation curve, winds were gusty, and vapor pressure deficit was low. Trunk water potential shows a greater than expected fluctuation.

One may interpret the cyclical nature of ψ_T in Figure 12 as being indicative of transpiration patterns since theoretically internal water potential is solely dependent upon the rate with which water is removed from the tree (transpiration) and the rate with which water enters the root system. Assuming a reasonably constant absorption rate, changes in ψ_T would directly reflect changes in transpiration.

An example of correlation between ψ_T and transpiration, as determined by the heat pulse method, is shown in Figure 13. Swanson (1967), also working with Engelmann spruce, found a diurnal cycle of sap velocity which, for clear days, assumed the characteristic shape as shown. Superimposed over the sap velocity curve in Figure 13 is the diurnal cycle of trunk water potential which occurred at the study site on August 10, 1971. Even with differences in location of the studies and times of the year, one may conclude that trunk water potential is inversely related to transpiration rate. It should be obvious at this point that a significant contribution to understanding plant-water relations could be made if further study would be made into defining more clearly the relations between sap velocity and internal water potential; perhaps even more meaningful would be a study of the relationship between sap velocity and water potential gradients, as such study could lead to a mathematical description of water potential gradients as a function of transpiration.

A surprising feature of the data presented in Figure 12 is the rate at which ψ_T is shown to rise and fall. Water potential in most cases falls slowly in the morning hours, drops rapidly to a short-lived minima around mid-day, then increases just as rapidly in the afternoon to early morning values. This suggests that water deficits in the tree occur for a relatively short period of time and are quickly alleviated by some mechanism which reduces transpirational loss. Stomatal action may be involved, but Figure 12 suggests that most of the time a simple physical reaction is involved--vapor pressure deficit fluctuates rapidly, and transpiration rate fluctuates rapidly in response to it.

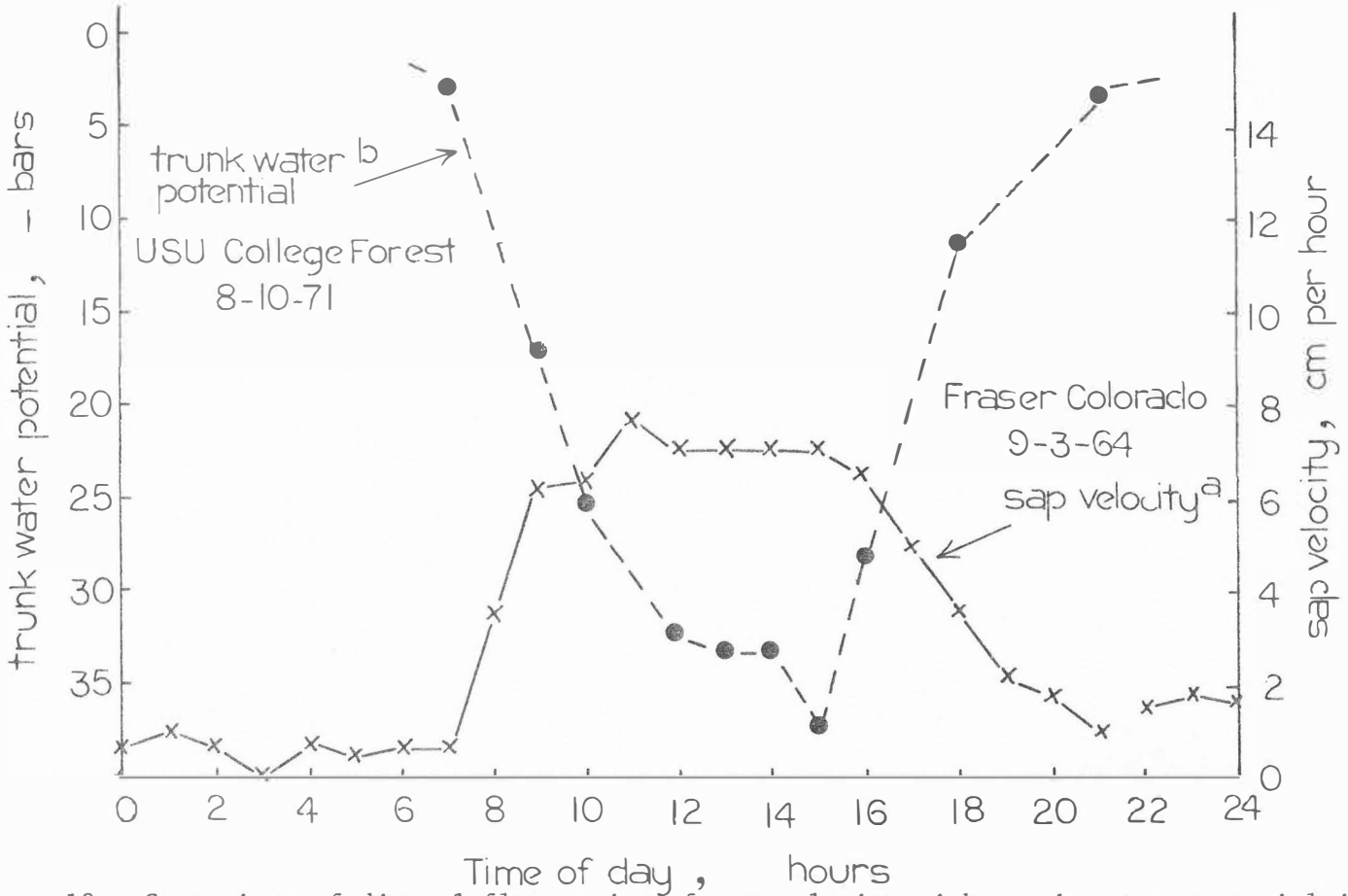

Figure 13. Comparison of diurnal fluctuation of sap velocity with trunk water potential in Engelmann spruce.

[a]Determined by the heat pulse method in a single Engelmann spruce tree (20 m tall) at 1.37 m height, after Swanson (1967).

[b]Mean water potential of 12 mature spruce trees determined by implanted psychrometers at 1 m height.

No nighttime measurements of ψ_T are given in Figure 12 because no voltage outputs in implanted psychrometers could be determined at these times. As such, ψ_T at night was probably between 0 and - 0.5 bar (- 0.5 bar is the highest water potential that can be accurately measured with thermocouple psychrometers). With no pressure potential in the tree trunk at night, it logically follows that osmotic potential of expressed sap may provide an estimate of water potential. Engelmann spruce branches were brought into the lab, sap was collected by use of the pressure chamber, and an estimate of osmotic potential made with a vapor pressure osmometer. Osmotic potential of expressed sap collected in this manner varied from practically 0 (pure water) to approximately - 0.3 bar.

A further complicating factor in trying to estimate ψ_T at night is that positive root pressures may be present. Thermocouple psychrometers do not measure positive water potentials. Root pressures may be sufficient to cause a positive water potential at one meter above the ground (height of psychrometers) since, at the study site, there is an abundance of stored water in the soil (Dr. H. H. Wiebe, personal communication, 1971).

The fact that ψ_T increased to high levels at night throughout the study period of diurnal variations suggests that soil water is not a limiting factor in the water relations of mature Engelmann spruce during summer at the study site. The "base level" of ψ_T would have risen late in the season when, if water was limiting, absorption of water into the roots would have been insufficient to meet the water deficit created during the day. This did not happen and, apparently, only short term water deficits occurred in the trees. Slatyer (1963)

speaks of a "base level" of water potential as being that which is determined after plant water potential has equilibrated with soil water potential. For equilibrium to take place, the plant cannot be actively transpiring. By this reasoning, soil water potential in the root zone of spruce at the study site should not have decreased below - 0.5 bar on the average. The shallow zones of soil did dry to water potentials appreciably below - 0.5 bar, but at a depth of 90 cm, soil water potential remained above the critical level of - 0.5 bar (see Table 14 of Appendix A). More details of soil water potentials measured at the study site are given in the section "Summer precipitation and the soil drying cycle."

The diurnal variation in stem water potential (ψ_S) is less pronounced than ψ_T and does not appear to be as highly correlated with solar radiation, wind, and vapor pressure deficit. Most stem samples were obtained from the branches of understory trees. These trees, for the most part, were not the same trees which were implanted with psychrometers, but those trees which were located in the immediate vicinity of each spruce plot. Such trees should not be expected to exhibit a marked diurnal pattern in ψ_S since they are highly sheltered from wind and shaded from radiation. Because of sampling differences, no attempt will be made to compare ψ_T with ψ_S.

Within-season patterns of water potential

Within-season patterns of water potential (both ψ_T and ψ_S) and selected environmental factors for the study period June 23 through October 12 are presented in Figure 14. Tabular values of ψ_T and ψ_S and environmental factors can be found in Table 18 of Appendix B.

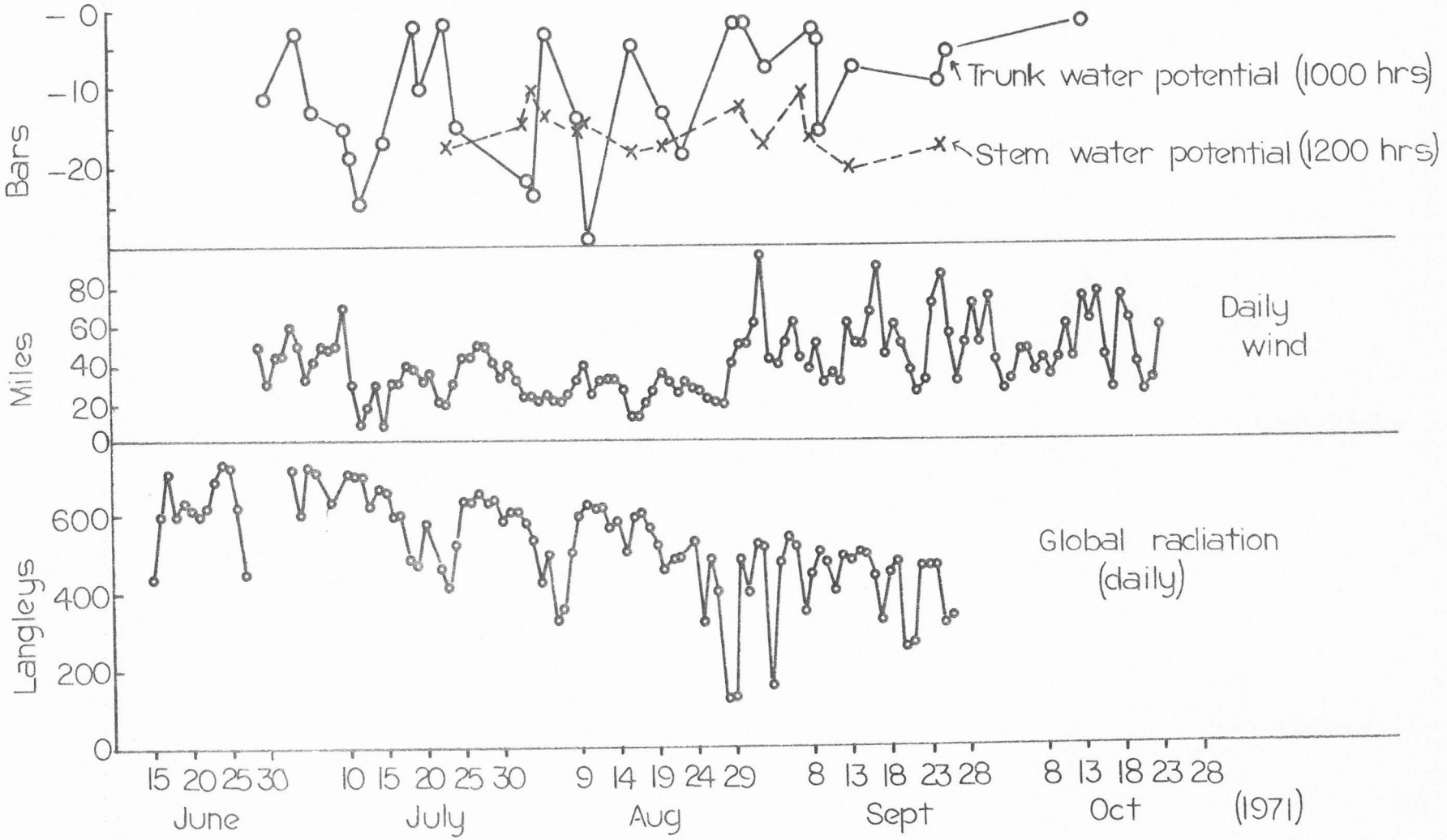

Figure 14. Seasonal variation of trunk and stem water potential in relation to some selected independent variables.

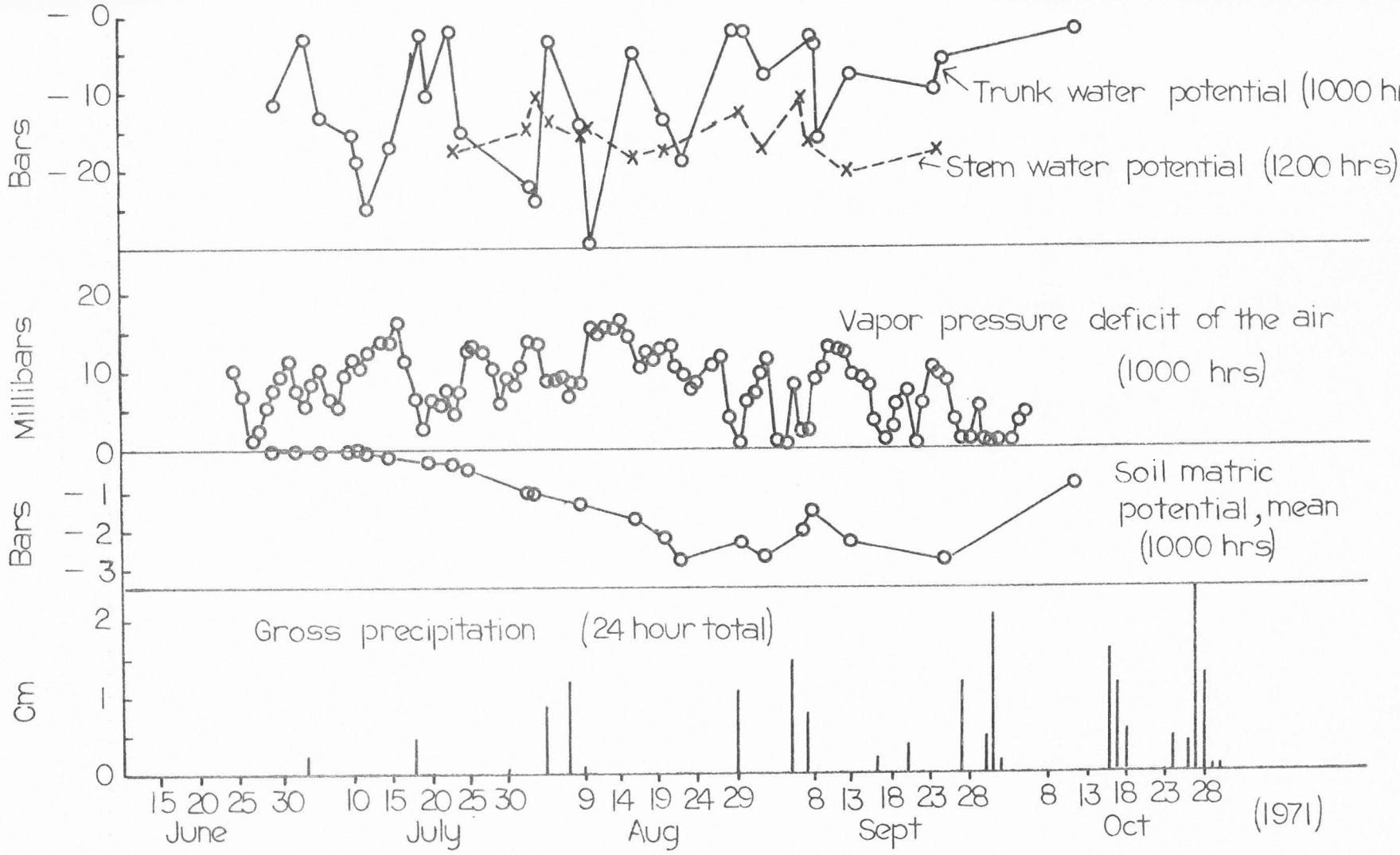

Figure 14. Continued.

Trunk water potential (ψ_T) varied greatly from measurement period to measurement period, being as high as - 1 bar and as low as - 30 bars. Plotted points in Figure 14 are a mean of 12 psychrometers for ψ_T and 20 pressure chamber determinations for ψ_S. Stem water potential (ψ_S), taken concurrently with ψ_T from about the middle of July through mid-September, also varied, but to a lesser extent than ψ_T measurements. Trends in ψ_S were similar to ψ_T, particularly for the last half of the data period.

Again, as was the case with diurnal measurements of water potential, atmospheric factors were more coincident with ψ_T than were soil factors. Of the atmospheric variables, vapor pressure deficit and gross precipitation appear highly correlated, and global radiation and wind speed less correlated with trunk water potential. Not surprisingly, periods of low vapor pressure deficit correlated with periods of rainfall (Figure 14). Also, periods of low vapor pressure deficit corresponded well with high water potentials (ψ_T particularly). Further examination of Figure 14 also shows that periods of high global radiation generally corresponded with periods of low water potential, while wind speed did not appear to have any consistent relation to water potential. As shown in Figure 14, soil matric potential does not appear to have any graphical relation to trunk or stem water potential.

As reported in the literature, the only comparative study of seasonal fluctuations in water potential of Engelmann spruce was that of Lindsay (1971). Lindsay reported his work with leaf water potentials of Engelmann spruce and subalpine fir in Wyoming. Samples were taken at a height of 1.5 to 3 meters between 1100 and 1300 hours, and the Schardakov dye method was used to determine leaf water potentials.

A comparison of short-term fluctuations in water potential with this study cannot be done as the data graphed in Lindsay's paper is not on a fine enough scale. If leaf water potentials determined by the Schardakov dye method can be compared to stem water potential obtained with the pressure chamber, a rough comparison of Lindsay's data with this study can be made. Lindsay states that at 2,990 meters elevation, the average water potential of mature Engelmann spruce needles was - 14 bars. At the College Forest stem water potential averaged - 17 bars during the hours 1000 to 1200 in mid-summer showing general agreement with Lindsay. Leaf water potentials in Lindsay's data ranged from - 10 to - 20 bars during the summer months. The range of stem water potentials as presented in Table 18 of Appendix B is - 10.9 to - 20.4 bars for the months of July and August, again showing good agreement.

The fact that water potential in the trunk rose to high levels (- 0.5 bar or greater) on many occasions throughout the 1971 study period leads to the conclusion that transpiration, on a seasonal basis, also fluctuates greatly and practically ceases during rainy periods (Figure 14). One would expect that, if trunk water status (ψ_T) was heavily dependent upon transpiration and if transpiration in turn determined sap velocity, sap velocities in Engelmann spruce would vary from zero flow to high rates of flow depending upon summer weather patterns. This has been shown to be really the case (Swanson, 1967). Swanson found sap velocities in Engelmann spruce to vary in much the same manner as trunk water potential did at the study site. For instance, Swanson found sap velocity to vary from 9.5 to 0.5 cm per hour in a period of only three days. Fluctuations in sap velocity were shown to correlate well with weather conditions at the time of

measurement. One can note in Figure 14 that ψ_T can vary from - 0.5 bar to - 20 bars within a three-day period, demonstrating also that ψ_T varies in the same manner as sap velocity. Swanson's work, although admittedly dealing with a different parameter, greatly strengthens the experimental data (both diurnal and within-season measurements of ψ_T) reported in this dissertation as it gives further evidence of the close relation between internal water potential with transpiration rate.

Evaluation of a Linear Effect Model

Proposed model

Data presented in Figures 12 and 14 strongly suggested that a functional relation exists between ψ_T and environmental variables such as vapor pressure deficit, radiation, and wind speed. Since trunk water potential measurements made according to the within-season schedule (1000 to 1130 hours) actually represented a small segment of the diurnal cycle for a particular day, it seemed logical that a predictive model could be developed (based on both sets of data) which would enable predictions of ψ_T to be made any time of any day. Scatter diagrams on linear and log scales of the relation between ψ_T and each of the closely related independent variables were constructed. The following linear effect model was proposed:

$$y = a + bX_1 + cX_2 + dX_3 + e\text{Exp } \log_{10} X_3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where:

y = water potential, negative bars,
a = dummy variable,
X_1 = radiation input, in langleys,
X_2 = wind, in miles, and
X_3 = vapor pressure deficit of air, in millibars.

Vapor pressure deficit of the air (vpd) was calculated by the equation:

$$vpd = (1.00 - rh)\ vps \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where:

rh = relative humidity in decimal fraction, and
vps = vapor pressure of saturated air at the ambient air temperature.

The transformation Exp $\log_{10}$ vpd was devised to linearize the relation between ψ_T and vapor pressure deficit.

Diurnal and seasonal predictive equations

The nature of the collected experimental data imposed the necessity that, although one model would apply, two separate sets of regression coefficients (hence two predictive equations) would need to be determined. The principal problems were with wind and radiation data. Wind movement was recorded hourly during the days in which hourly variations in ψ_T were measured, but only daily at all other times. As a result, wind movement by hour was used as the input variable in the diurnal prediction equation and wind movement by day was used in the within-season predictive equation. A lack of resolution in the time scale of the bimetallic actinograph made it difficult to obtain a reliable estimate of radiation for any instantaneous point in time. Earlier it was shown that the average time lag between radiation peaks and minimum water potentials was about two hours. Logically, then, radiation input two hours previous to a ψ_T measurement would be the form of the radiation variable. Since this could not be done for the within-season prediction equation, total radiation input the day of the measurement was used as an input variable. Radiation input two hours

previous to a ψ_T measurement was used in determining the radiation coefficient in the diurnal predictive equation since the effect of an error at one data point would likely be offset by data from other hours.

Multiple regression analyses were performed with the aid of an IBM System 360/44 computer at Utah State University to evaluate the proposed model and determine coefficients for diurnal and within-season predictive equations. The results of these analyses are given in Tables 10 and 11.

All proposed variables in the diurnal prediction equation (Table 10) were highly significant with the exception of wind movement. Variables X_3 and X_4 were intercorrelated as expected, but both variables

Table 10. Analysis of variance of diurnal water potential model (ψ_T).

Source of variation		Degrees freedom	Mean square	F-ratio	Coefficients
description	sym-bol				
Dummy	(X_0)				4.9317
Radiation[a]	(X_1)	1	118.14	4.69*	- 4.7158
Wind[b]	(X_2)	1	52.45	2.08	- 0.7719
Vapor pressure deficit[c]	(X_3)	1	265.00	10.52**	- 0.8969
Exp $\log_{10} X_3$[d]	(X_4)	1	310.79	12.33**	$- 4.1386 \times 10^{-5}$
Model		4	524.03	$R^2 = 0.812$	
Error		56	25.19		
Total		60	125.12		

[a]Global radiation (ly min^{-1}) 2 hours before a measurement.
[b]Average miles of wind which occurred 1 hour preceeding a measurement.
[c]In millibars at the time of measurement.
[d]Transformation which attempts to account for the fact that increasing vpd has little effect on ψ_T until it reaches a critical value; thereafter, the effect is ever-increasing.

were left in the regression because removal of either lowered the coefficient of determination (R^2) by 0.04. Note in Table 10 that all variables have a negative coefficient, meaning that as each variable is increased, ψ_T becomes less (more negative). In other words, each variable contributes to a negative water potential. Vapor pressure deficit was a highly significant variable as anticipated in Figures 12 and 14.

Only the variable X_3, vapor pressure deficit, was significant in the regression for determination of the within-season water potential prediction equation (Table 11). Radiation, wind, and the transformation

Table 11. Analysis of variance of the within-season water potential model (ψ_T).

Source of variation		Degrees freedom	Mean square	F-ratio	Coefficients
description	symbol				
Dummy	(X_0)				- 9.0176
Radiation[a]	(X_1)	1	27.08	1.26	- 0.0116
Wind[b]	(X_2)	1	25.46	1.19	- 0.0497
Vapor pressure deficit[c]	(X_3)	1	217.03	10.12**	- 3.1332
Exp $\log_{10} X_3$[d]	(X_4)	1	63.26	2.95	11.9621
Model		4	315.45	R^2 = 0.719	
Error		23	21.44		
Total		27	64.00		

[a]Global radiation, total langleys received during the measurement day.
[b]Total daily wind in miles which occurred on the day of measurement.
[c]In millibars at the time of measurement.
[d]Transformation which attempts to account for the fact that increasing vpd has little effect on ψ_T until it reaches a critical value; thereafter, the effect is ever-increasing.

of vapor pressure deficit were not significant but, as a whole, they contributed several percent to the total R^2 values. Such variables were not removed from the predictive equation of within-season trunk water potential. A possible reason for lack of significance of radiation and wind variables may have been the quality of input data. Despite the lack of significance, all variables with the exception of Exp $\log_{10} X_3$ contributed to a negative water potential.

Evaluation of the proposed model

The coefficients determined by multiple regression analysis were entered into the proposed model (Equation 3) and trunk water potential was predicted for both diurnal and seasonal data sets. Predicted versus observed ψ_T values are plotted in Figure 15. For the diurnal water potential cycles, the predicted lines match the observed values well on all days except September 8. On September 8 radiation levels were high (Figure 13), but some mechanism (stomatal closure perhaps) prevented a high transpiration rate and trunk water potentials remained high. On some of the clear sky days, the model did not predict as low mid-afternoon water potentials as were observed. This is not as serious as it would seem and quite likely it results from the failure of the model to include all factors which determine the response of the dependent variable, ψ_T. It should be pointed out that peaks and lows of predicted versus observed values are in phase; an out-of-phase condition between observed and predicted is often a problem when using multiple regression analysis, but it was not in this analysis. The proposed model fit seasonal patterns of water potential well during early and late summer, but during mid-summer it was not as responsive

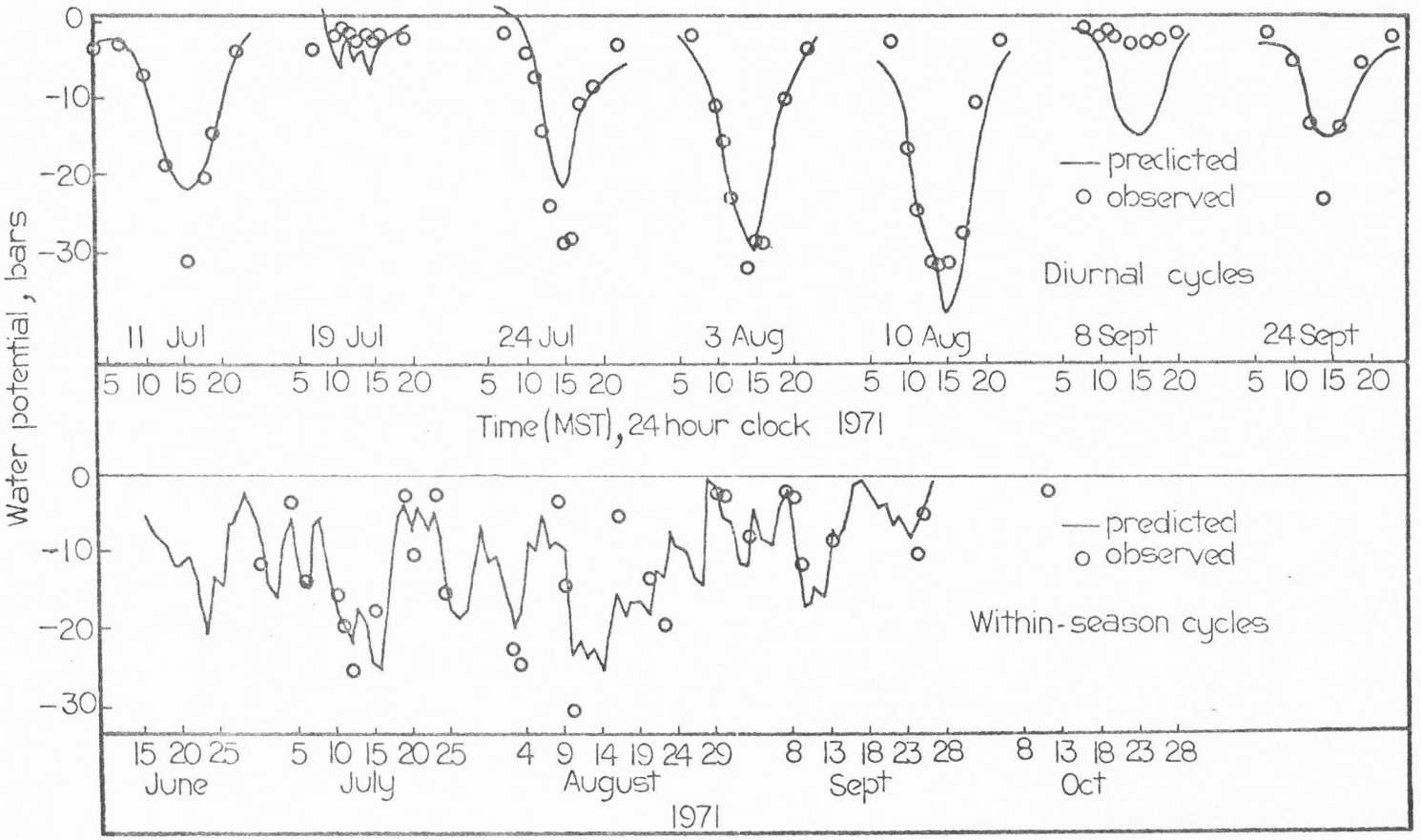

Figure 15. Comparison of observed versus predicted diurnal and within-season cycles of trunk water potential.

to fluctuations as were shown by observed values. Again, the lack of response of the predictive model, at times, was probably due to the failure of the model to represent the real life situation. Roughly 28 percent of the variation in water potential was not explained, and undoubtedly, this unexplained variability is responsible for shortcomings in the predicted variable, ψ_T.

In evaluation of the proposed linear effect model, two points should be emphasized. First of all, this is a "first order" model to predict trunk water potential and is subject to modification in future work. The nature of the model was limited by the accuracy, or quality, of the data that could be obtained and the information that is currently known about the transpiration process. When more information is acquired concerning the relation between transpiration and trunk water potential in Engelmann spruce trees and when environmental variables can be measured in the canopy where they are causally related to transpiration, the proposed model can be modified, perhaps changed completely. One serious constraint in this study was that relative humidity could only be measured at ground level and the assumption had to be made that humidity fluctuations at the bottom of the spruce stand corresponded with fluctuations in the canopy where actual transpiration was taking place. Secondly, the proposed linear effect model does not necessarily describe the "cause and effect" relation between ψ_T and variables in the model. It seems likely that vapor pressure deficit, radiation, and wind are causally related to ψ_T, but I do not have proof of this, nor do I have proof that a linear model would represent the true-to-life situation had I known all factors which were responsible in determining trunk water potential. Still, with the reservations stated above, the

proposed model predicts trunk water potential accurately enough that we now have some insight into how Engelmann spruce reacts to its environment with respect to water relations.

The multivariate analysis as presented above is not meant to replace some of the existing, well-established evapotranspiration models; but rather, it is presented as an attempt to statistically explain variability in observed internal water stress. The analysis may help to evaluate the reaction of Engelmann spruce to its environment in contrast with other vegetation.

Some discussion can be made relating results of the multivariate analysis to Penman's approach to predicting potential evapotranspiration from a vegetative canopy (Penman, 1956). The Penman equation uses the combination method, which employs both energy budget and aerodynamic approaches. Net radiation has been shown to be the most important variable with wind travel and vapor pressure deficit as having important, yet lesser roles. Results of the multivariable equations suggest that more study be done before routinely applying Penman's method (or other empirical methods) to the prediction of water losses from a mature stand of Engelmann spruce. Vapor pressure deficit, for example, had a prominent role in explaining changes in internal water potential. It is apparent from climatic data in Figure 14 that periods of high and low water potential would coincide with periods of low and high potential evapotranspiration. The amount of disagreement between observed water stresses and potential evapotranspiration estimates would depend upon many factors: (1) the relation between water stress (water potential) and actual evapotranspiration losses, (2) sensitivity of the Penman equation to fluctuations of vapor pressure deficit observed at

the study site, (3) accuracy and representativeness of climatic variables which were measured, and (4) the degree to which the study sites meet the requirements of Penman's equation--namely a dense vegetative canopy and no limiting soil water. To sum discussion of the point, a logical outgrowth of the present study would be to objectively evaluate current methods which predict the water economy (evapotranspiration) of vegetative communities with respect to insights which have been obtained into the internal water potential of Engelmann spruce.

Summer Precipitation and the Soil Drying Cycle

Rainfall, throughfall, and interception

Estimates of rainfall, throughfall, and interception were made at the study site during the summer months of 1970 and 1971. From July to September of 1970, rainfall was measured in 12 #10 cans in the meadow area and in 9 #10 cans at spruce plot 1. Analysis of data that summer showed no significant difference between rainfall catch in the standard 8-inch (20.3 cm) gage at Tower climatic station and the 12 #10 cans which were placed on the ground in the meadow, so that during the summer of 1971, the #10 can network at the meadow was discontinued and the recording gage was used as the only estimate of gross rainfall. During the summer of 1971, three more spruce plots were established and #10 cans were placed at each of these, resulting in a more reliable estimate of throughfall. A transect of seven cans running from west to east were placed across each spruce plot. Table 12 presents a tabulation of all individual summer storms which occurred during both 1970 and 1971 field seasons with estimates of gross rainfall, net rainfall,

and percent interception. It appears from these storms that roughly 0.25 cm of rain must fall before interception storage of the canopy is satisfied and measurable amounts of rain can fall to the forest floor.

Table 12. Interception of summer rainstorms by an Engelmann spruce-subalpine fir stand at the Utah State University College Forest.

Date of[a] event	Gross[b] rainfall	Throughfall[c]	Interception	No. of cans	Coefficient[d] var.	Std. error[d] mean
	(cm)	(cm)	(%)		(%)	(cm)
7-06-70	0.25	0.00	100	3		
7-07	0.38	0.02	95	3		
7-09	0.30	0.01	97	3		
7-10	0.25	0.13	48	3		
7-27	0.63	0.27	57	9	98	0.09
8-31	0.63	0.23	64	9	100	0.08
9-06	3.68	4.06		9	28	0.37
9-20	0.51	0.25	51	9	58	0.05
7-04-71	0.25	0.01	96	27		
7-18	0.51	0.11	78	27	76	0.003
7-30	0.05	0.00	100	27		
8-04						
(0500)	0.08	0.01	87	27		
(1300)	0.79	0.16	80	27	104	0.04
8-07	1.17	0.46	61	28	78	0.07
8-09	0.05	0.00	100	28		
8-29	1.14	0.63	44	28	59	0.07
9-05	1.50	0.93	38	28	50	0.09
9-07	0.81	0.48	40	28	67	0.06

[a]Six hours of no rain defined a minimum break between storms.
[b]Measured by standard 8-inch gage located in a meadow area.
[c]Measured in #10 cans after dripping had ceased
1970 - one plot, 154 meters^2,
1971 - four plots, each 154 meters^2.
[d]Of throughfall

The large amount of variability among sample catches of a given storm was expected since canopy closure and density at the study site are highly irregular--as one would expect to find in an all-aged stand.

With the data presented in Table 12 and assuming that gross precipitation was evenly distributed through the study area, a least squares fit of a parabola was calculated (a plot of net rainfall versus gross appears parabolic rather than linear). The following equation was determined:

$$y = -0.02 + 0.20 X + 0.28 X^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where:

y = throughfall (at forest floor) in centimeters, and
X = gross precipitation in centimeters.

Comparison of the throughfall-gross precipitation relationship found in this study for Engelmann spruce with other data reported in the literature is difficult because of the varied methods in which data from other studies were collected and mathematically presented. A comparison of the results shown in Table 12 with that reported by Rothacher (1963) for Douglas-fir is given in Table 13 since both studies are concerned with interception in natural, mature stands of conifer. This

Table 13. Comparison of percent interception by rainfall classes between a dense canopy of mature, Engelmann spruce and a canopy of old-growth Douglas-fir.

Species	Gross rainfall classes (in cm)				
	0-0.13	0.13-1.3	1.3-2.5	2.8-3.3	3.8-5.1
Douglas-fir	100	32	23	21	19
Engelmann spruce	96	70	38	--	--

comparison shows that, for the 0.13-1.3 and 1.3-2.5 rainfall classes at least, Engelmann spruce intercepted a larger proportion of the gross precipitation than Douglas-fir, but it is difficult to determine whether these differences are significant since the percent intercepted is dependent upon the canopy density and configuration at each of the study sites.

Patterns of soil matric potential

Replication of soil water potential measurements the second summer of the study enabled a comparison to be made of mean soil matric potential between two contrasting vegetative types and two distinctly different soil drying cycles (Figure 16). A direct comparison of 1970 and 1971 curves of soil matric potential (Figure 16) cannot be made since the sampling points were not at the same locations both years; however, the differences which do appear in the meadow drying curves seem to be too large to be attributed to sampling differences alone. Snowfall during the 1970-1971 winter was unusually heavy (93.6 cm water peak accumulation) and coupled with a cold, cloudy spring, the snowpack lasted roughly two weeks later into the summer than it did the year before. As a result, the soil water depletion period was shorter, less evaporation from the soil took place, and soil matric potentials did not reach as low levels in 1971 as in the summer of 1970. The effect of the longer soil water depletion period in 1970 is particularly pronounced in the matric potential curve at the meadow (Figure 16). Here the average soil matric potential dropped to much lower values in 1970 than it did in 1971. Further evidence for differences in soil drying curves (at the meadow) between 1970 and 1971 can be seen in the

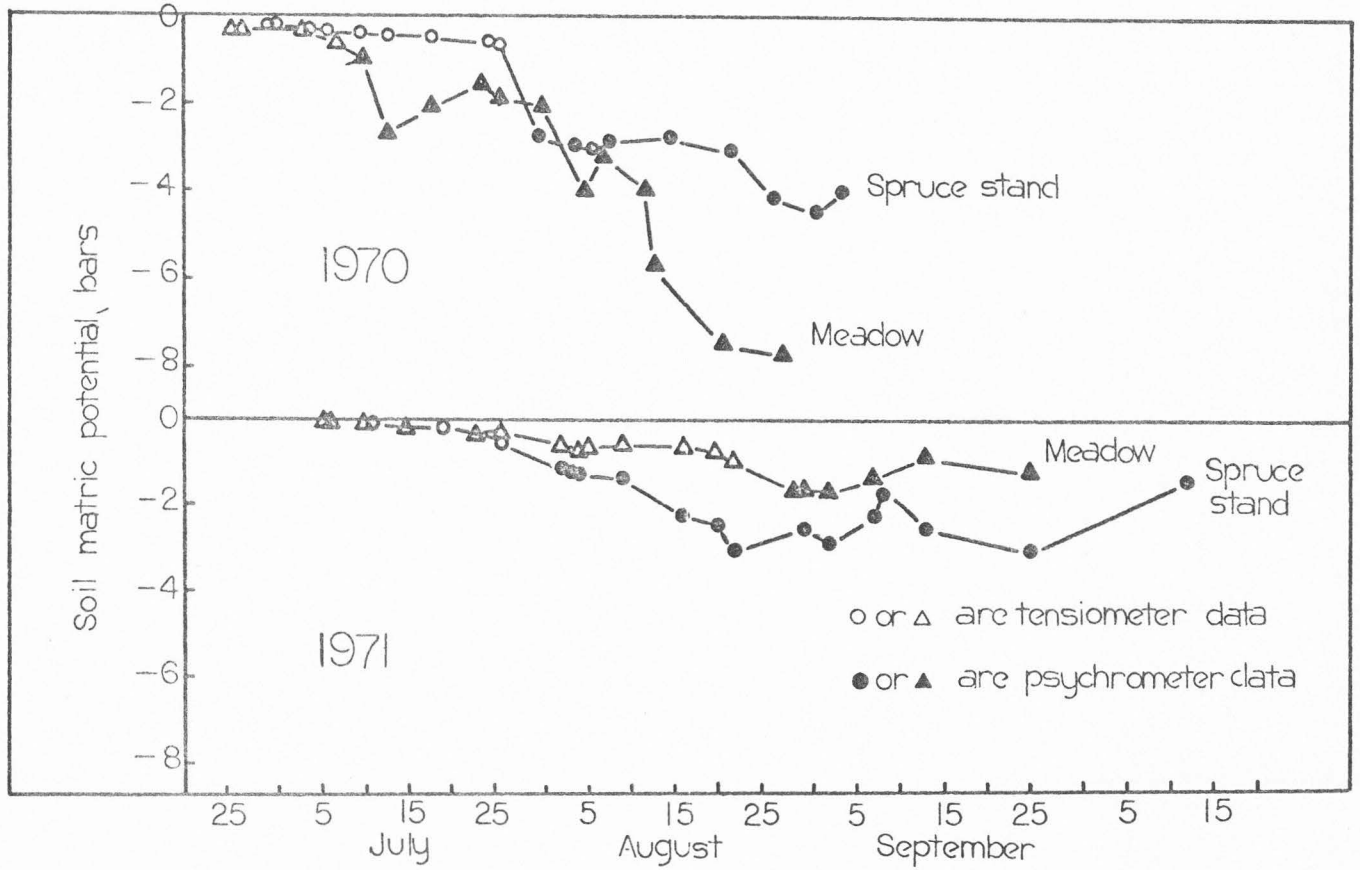

Figure 16. Comparison of the mean soil matric potential between meadow and spruce plots during the summer months of 1970 and 1971. Each plotted position is an average of four depths--15, 30, 45, and 90 cm.

soil water content data in Tables 15 and 16 of Appendix A. Soil water content at the 15 cm depth (most directly influenced by evaporation) was greater in 1971 than in 1970 at all times of measurement from July 2 to September 6. The volumetric water content at the 15 cm depth on September 3, 1970 was 6.0 percent, while on September 6, 1971 at the same depth it was 13.0 percent. One must remember that a longer soil water depletion period can result in greater transpiration as well as direct soil evaporation; therefore, the magnitude of difference between soil matric curves in the meadow (Figure 16) may not be due to an increase in direct soil water evaporation alone. The curves of soil matric potential in the spruce stand do not show large differences between 1970 and 1971. The soil water content data of spruce plot 1 in Tables 15 and 16 of Appendix A show that more water was present at the 15 cm depth in June of 1971 than June of 1970. The difference between the two years is rapidly diminished, and by early September there is no difference in soil water content between the two years.

The change of soil matric potential with depth and time of year at the spruce stand in 1970 was similar to that found in 1971 (Figures 17 and 18). Soil matric potential at the 15, 30, and 45 cm depths remained distinctively lower than the 90 cm depth throughout the summer months of both 1970 and 1971. Figures 17 and 18 strongly suggest that soil water was not heavily withdrawn from any single soil zone, but from throughout the measured soil profile. If most soil water was withdrawn by tree roots at the 15 cm depth, for example, one would expect a continual increase in matric potential as depth in the soil increased. Besides an increasing gradient in matric potential, one would expect to find soil matric potentials at a given depth in the same relative

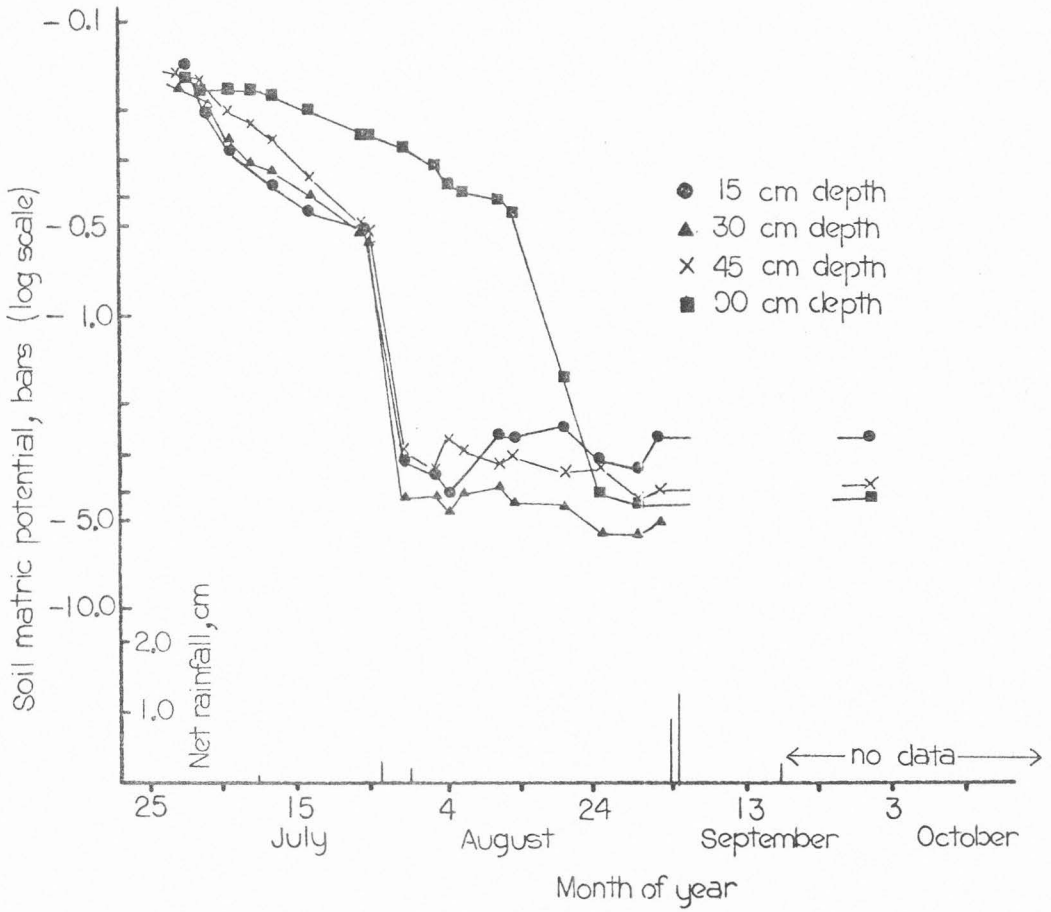

Figure 17. Soil matric potential and net precipitation at spruce plot 1 during the summer of 1970.

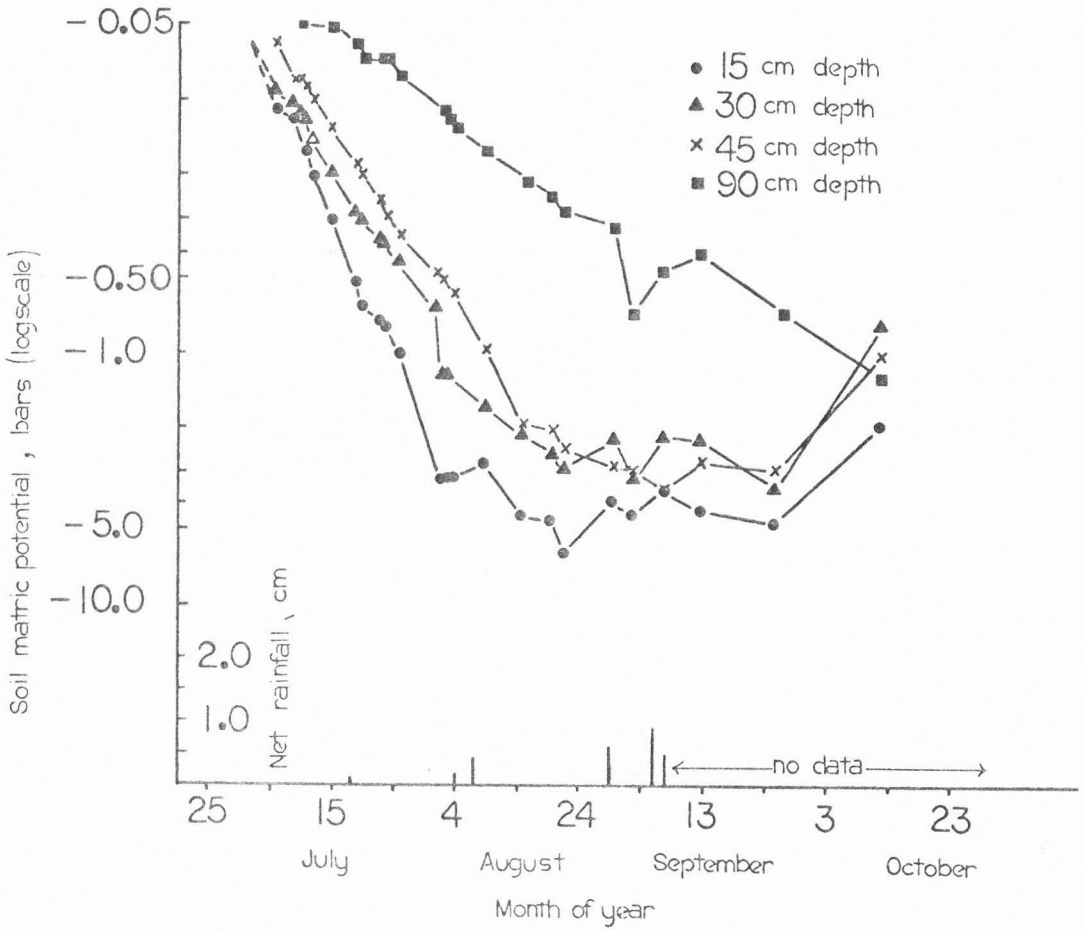

Figure 18. Mean soil matric potential and net precipitation at spruce plots 1, 2, 3, and 4 during the summer of 1971.

position with one another. This was not the case. In both 1970 and 1971, the 15, 30, and 45 cm curves started out in late June with 15 cm the lowest potential, 30 cm slightly higher in potential, and 45 cm the highest potential; but by mid-August, the curves began to overlap and become intermingled. Overlapping of soil matric potential curves would not be likely to happen if water were being withdrawn from a single zone in the soil; since uniform matric potential gradients were not measured throughout the summer months, one can conclude that tree roots are withdrawing water from the 15, 30, and 45 cm depths at least sometime during the soil water depletion cycle. Soil matric potential at the 90 cm depth remained much higher than the other measured depths during most of the summer months of 1970 and 1971 (Figures 17 and 18). A continually dropping matric potential at this depth indicates that water is being removed, either directly by tree roots or by flux in response to a matric potential gradient. Since matric potential generally increased with increased soil depth, water probably moved from the 90 cm depth toward the surface. It is likely that some of the drop in matric potential at the 90 cm depth resulted from direct absorption, since some roots were found at this depth in the soil pit at spruce plot 1. Some neutron probe access tubes were installed at the study area to depths exceeding 90 cm. In general, little change in water content was measured at these depths.

The effect of fall precipitation on soil matric potential is shown in Figure 18. Soil matric potential at the 15, 30, and 45 cm depths increased from roughly - 5 bars to - 1 bar or greater, from late September to mid-October, 1971. Note that soil matric potential at the 90 cm depth was unaffected, meaning that precipitation inputs did not

reach that depth. No net precipitation data are presented in Figure 19 after September 7 since the precipitation that fell was in the form of snow and could not be accurately measured. The snow which did fall between September 7 and October 12 melted (see Figure 19 for gross precipitation) and at least some of it entered the soil. The effect of precipitation input on soil matric potential in 1970 (Figure 17) was not shown. A possible reason that increased matric potentials were not measured here was that too much time elapsed between major early September inputs and the last measurement of soil matric potential. During this time interval, appreciable amounts of soil water may have been lost to evapotranspiration.

The effect of rain on matric potential at the shallow soil depths of the meadow area was more evident during the summer of 1971 (Figure 19) than during the summer of 1970 (Figure 20). Fluctuations in soil matric potential were greater in the shallow soil depths at the meadow area than they were under the spruce canopy. The probable reasons for greater soil matric potential fluctuations were (1) precipitation inputs were much greater since there was no overstory of trees to intercept water and (2) the soil surface was much more exposed to drying winds and solar radiation. In both Figures 19 and 20, matric potential fluctuations at the 5 and 15 cm depths are shown to be affected by precipitation inputs while the 30 cm depth is much less affected. The most significant information that is provided by data given in Figures 19 and 20 is that the soil environment in the 0 to 15 cm depth is particularly harsh for plant growth and development with matric potentials changing from field capacity to - 20 bars in time periods as short as two weeks. It is easy to see that a plant whose roots are

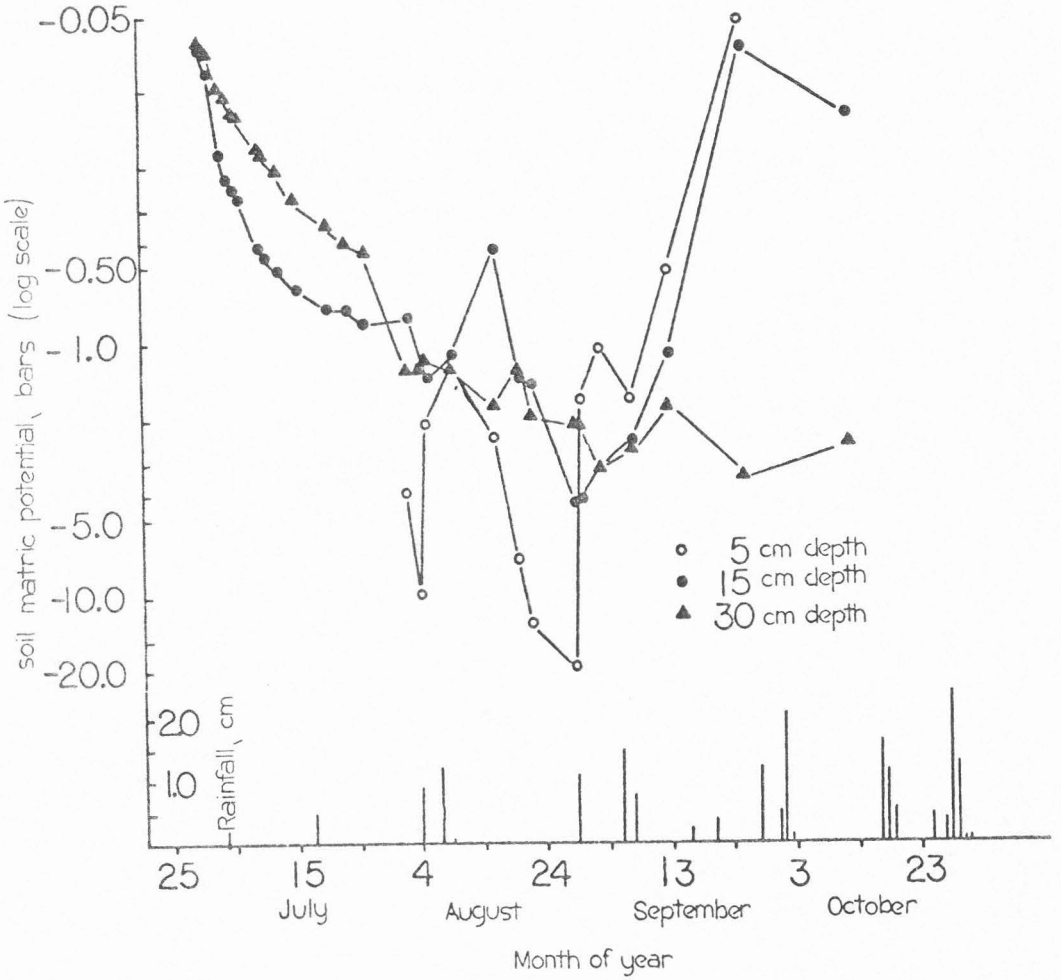

Figure 19. Mean soil matric potential and gross precipitation at meadow plots 1 and 2 during the summer of 1971.

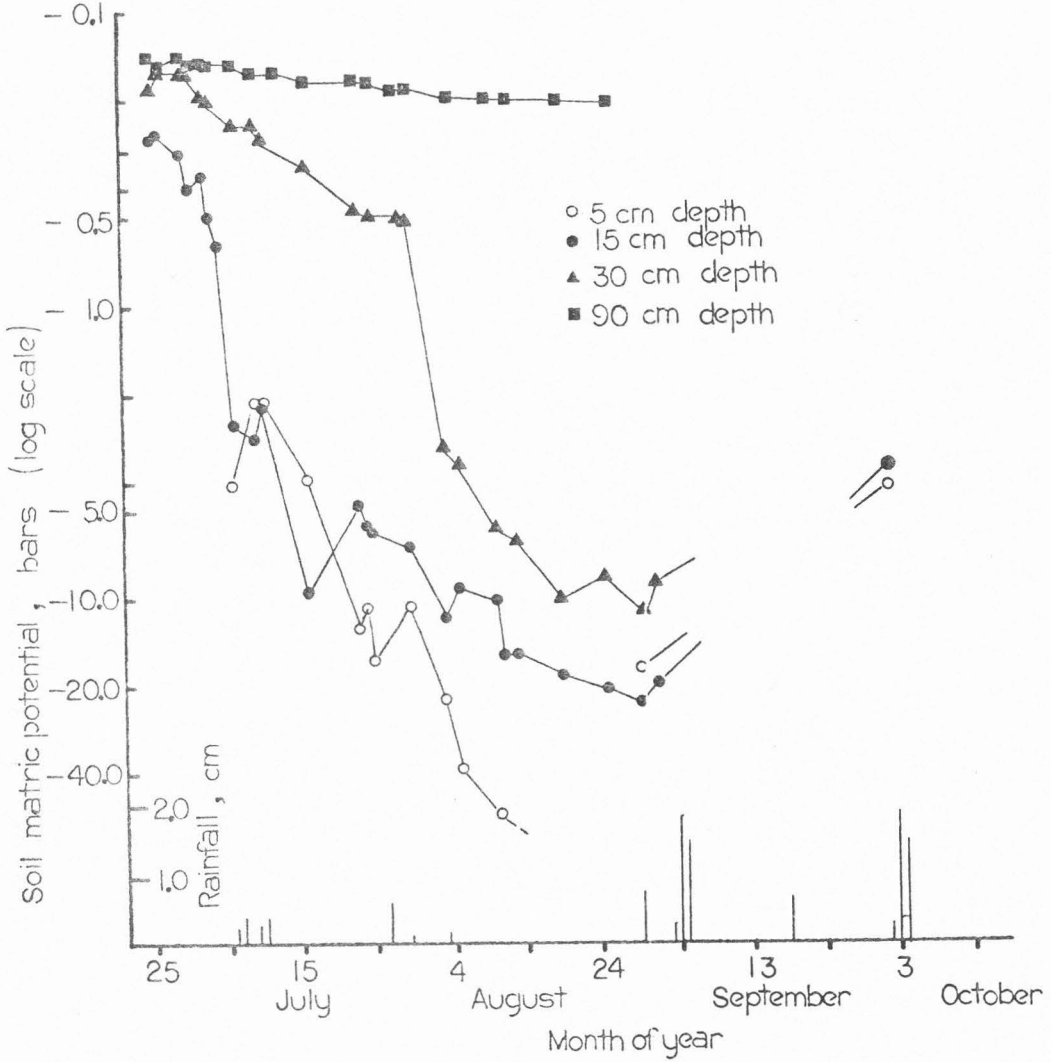

Figure 20. Soil matric potential and gross precipitation at meadow plot 1 during the summer of 1970

limited to this habitat would need to germinate and complete its life cycle in only a few weeks if it were to successfully reproduce itself. For spruce seedlings to survive, roots would need to grow to depths exceeding about 15 cm in a short period of time. Large plants which develop roots to deeper depths would have a more regulated soil environment since matric potentials at depths greater than 15 cm do not fluctuate nearly so greatly as the shallow depths and remain well below - 15 bars, the wilting point for many plants.

Inferring depth of rainfall penetration

A rainy period commencing the morning of August 29, 1971 made it possible to demonstrate the usefulness of thermocouple psychrometers in detecting rapid changes in soil matric potential as might be expected to take place with infiltrating water. Figure 21 shows the results of this particular storm. Matric potential at the 5 cm depth at meadow plots 1 and 2 rose rapidly between 0700 and 1800 hours on August 29. Matric potential at the deeper depths was unaffected. The effect of the rain was still evident on August 30 as matric potential at the 5 cm depth was greater than the 15 and 30 cm depths, a reversal of the earlier situation.

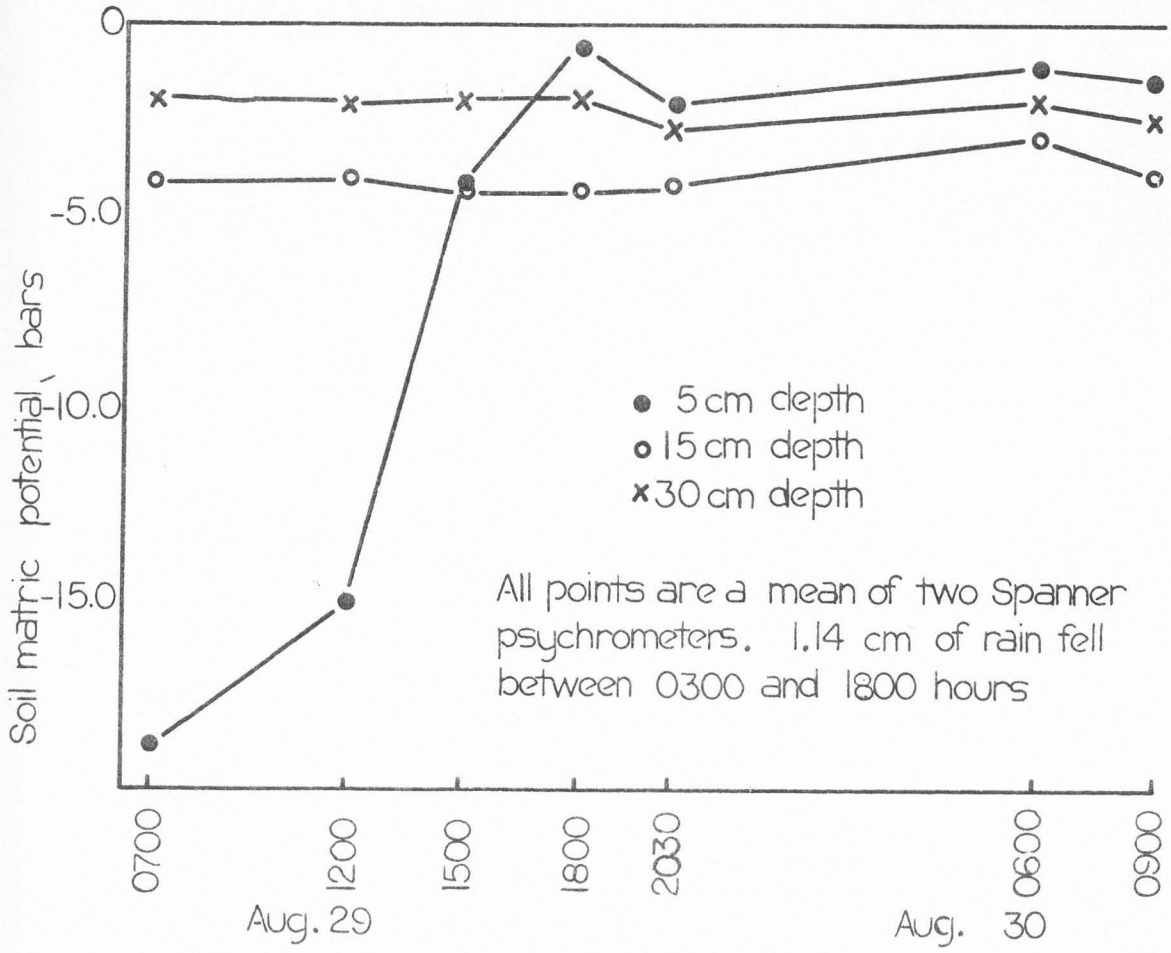

Figure 21. Change in soil matric potential in the open meadow following a rainy period beginning the morning of August 29, 1971.

SUMMARY AND CONCLUSIONS

The primary objective of this study was to determine the degree of correlation between internal water potential of Engelmann spruce trees and selected environmental factors. In order to more clearly understand the variations in internal water potential, within-season and diurnal trends were investigated. A linear effect model relating measured water potentials with independent atmospheric factors was developed.

The secondary objective of the study was to determine the effect of summer precipitation, both in meadow and forested sites, on the soil drying cycle. By use of throughfall gages, an estimate was made of the relation between magnitude of storms and net precipitation under a canopy. Water potential fluctuations in the soil were studied in relation to amounts of precipitation.

Four study plots (each roughly 154 square meters) under spruce cover and two study plots (100 square meters) in a small meadow were established. At each spruce plot, a thermocouple psychrometer was installed at one meter above the ground on the north side of three selected, mature Engelmann spruce trees. Thermocouple psychrometers were installed at 5, 15, and 30 cm depths in the soil at the meadow plots and at 15, 30, 45, and 90 cm depths at the spruce plots. A tensiometer and two soil temperature thermocouples were installed near the thermocouple psychrometers at each of the plots but at 15, 30, 45, and 90 cm soil depths. Throughfall gages were placed at each plot to obtain an

estimate of rainfall which was not intercepted by the canopy but which fell to the forest floor.

Gross precipitation was measured by a 20.3 cm diameter recording gage located at the meadow. Global radiation and wind were recorded at the meadow area also. Air temperature and relative humidity were recorded in wooden shelters. One shelter was located at the meadow area and one was located in the vicinity of the four spruce plots.

Except for wind, weather parameters were recorded continuously. Wind was totalized on a digital counter and recorded on data sheets when needed. Psychrometric, pressure chamber, and soil data were obtained according to two schedules. Diurnal measurements of trunk water potential and independent variables were made during seven days in the summer months of 1971 on six trees. Seasonal measurements of the latter were done on twelve trees at periodic intervals during the summer averaging every three to four days. Data to evaluate the effect of summer precipitation on the soil drying cycle was obtained periodically the summer of 1970 and concurrently (for the most part) with tree water potential measurements during 1971.

Significant findings of this study included the following: as shown by analyses of variation of the data, within-season variations of tree water potential (by psychrometer and pressure chamber measurements) were statistically significant. In other words, fluctuations in water potential with time were large enough that they could not have been due to chance alone.

On an hourly basis for seven cycles of diurnal measurements, daily peaks in wind movement corresponded roughly with trunk water potential minima, peak radiation occurred about two hours before water potential

minima, and maximum vapor pressure deficits corresponded closely to water potential minima. Diurnal fluctuations in water potential of small understory branches, as determined by the pressure chamber, did not correlate well with weather factors.

Seasonally, trunk water potential appeared to be highly correlated with fluctuations in vapor pressure deficit and less correlated with global radiation and wind movement. Soil factors such as matric potential and temperature were not correlated with trunk water potential. Correlations between water potential determined by the pressure chamber and environmental factors were not consistent. Pressure chamber values of water potential, however, did correlate roughly with trunk water potential during the latter half of the summer of 1971.

Based on scatter diagrams of the relation between trunk water potential and recorded independent variables, a linear effect model was proposed. It was of the form:

$$y = a + bX_1 + cX_2 + dX_3 + e \text{ Exp } \log_{10} X_3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where:

y = water potential, negative bars,
a = dummy variable
X_1 = radiation input, langleys,
X_2 = wind, in miles, and
X_3 = vapor pressure deficit of the air, in millibars, and
b, c, d, and e are regression coefficients.

The transformation Exp $\log_{10} X_3$ was devised to account for the non-linearity between vapor pressure deficit and trunk water potential.

The proposed model (Equation 6) was evaluated by multiple regression analysis and a predictive equation was devised to predict trunk water potential on a daily and on a seasonal basis. With diurnal input data, radiation, vapor pressure deficit, and the transformation of

vapor pressure deficit were significant variables. The proposed model explained 81 percent of the diurnal variation in trunk water potential. Evaluation of the model with seasonal data input showed only one variable, vapor pressure deficit, highly significant. With seasonal data, 72 percent of the variation in trunk water potential was explained. The discrepancy between diurnal and seasonal evaluations of the model was suspected to be a result of differences in data quality.

Analysis of 18 rainstorms which occurred during two summers of study showed that roughly 0.25 cm of rain must fall before interception storage of a spruce canopy is satisfied and measurable amounts of rain can fall to the forest floor. Variability among sample catches of a given storm was great, apparently reflecting the irregular nature of the overmature spruce canopy. On the average, 96 percent of rainfall from storms between 0.00 and 0.13 cm, 70 percent between 0.13 and 1.3 cm, and 38 percent between 1.3 and 2.5 cm was intercepted. The influence of rain on soil matric potential was restricted to the first 45 cm of soil at the spruce plots with no substantial increase of matric potential before the onset of fall rains. The effect of rain on matric potential of soil in the meadow was more pronounced, particularly during the summer of 1971. The matric potential of the 5, 15, and 30 cm depths fluctuated greatly. A temporary increase in matric potential of these depths following summer storms was noted while more marked increases in matric potential were measured after heavier fall rains.

The major conclusions made as a result of this study are (1) water potential in the trunks of Engelmann spruce changes markedly from hour-to-hour and from day-to-day during the summer months, (2) trunk water

potential as measured by thermocouple psychrometers is functionally related to atmospheric factors of radiation, wind, and vapor pressure deficit, (3) fluctuations in trunk water potential with weather factors imply a causal relation with transpiration, (4) precipitation during the summer months modifies soil matric potential--but only in the shallow profiles, (5) matric potential fluctuations in meadow areas are extreme (from saturation to low as - 40 bars) and impose a serious threat to the water economy of young Engelmann spruce seedlings established in such meadows, and (6) Peltier type thermocouple psychrometers are useful instruments for investigation of the soil-plant-atmosphere continuum in field situations.

The findings of this research suggest at least one follow-up study to further investigate the relation between water potential, transpiration, and environmental factors. A relation, albeit a circumstantial one, has been implied between transpiration rate and trunk water potential. Also, this study showed that it is possible to measure changes in trunk and stem water potential throughout the soil-plant continuum. A significant contribution to the water relations field may be made by simultaneously measuring trunk water potential, stem water potential, sap velocity, and transpiration, and relating these variables to environmental factors obtained within the canopy. Such a study may elucidate the relations between transpiration and water potential, between transpiration and sap velocity, and improve upon the predictive model as reported in this dissertation. Some further consideration should be given to well-established evapotranspiration models (Penman's, for example) in view of findings as reported in this study.

INHERENT PROBLEMS OF MEASURING WATER POTENTIALS IN TREES AND SOIL

This section is a discussion of errors and problems of methodology involved in attempting to measure water potentials in trees and soil. Although this study was only concerned with Engelmann spruce, similar problems undoubtedly will be found with other species and study locations.

Thermocouple psychrometers

The inherent errors in measurement of water potential with Peltier psychrometers as outlined in Rawlins and Dalton (1967) are largely eliminated by miniaturization of components and insulation of the units from rapidly changing ambient temperatures. In this study, blocks of polyurethane foam prevented heat from being easily transferred down the lead wires and to the reference junctions within the thermocouple body. However, temperature gradients within the tree itself were nearly always present. Such gradients caused reference and wet-bulb junctions within the psychrometer to be at different temperatures. As a result, a "bucking voltage" needed to be applied to the thermocouple circuit to effectively "zero" the psychrometer. Zeroing each psychrometer before applying a cooling current offset any emf that existed between wet bulb and reference junctions. After this procedure, the psychrometers performed as expected, but the real effect of temperature gradients, which existed in the psychrometer at the time of measurement, was never really known. No correlation between air and psychrometer temperature

differences and measured water potentials was shown earlier, but this does not conclusively exclude temperature gradients within the psychrometer itself as a source of error.

From the experience of this study, measurements of soil matric potential appeared to be less subject to experimental error than measurements of water potential within the trees. Unlike tree installations, much of the psychrometer lead wires were buried in the soil, thus largely eliminating the chance of heat being conducted into the psychrometer body. Soil psychrometers were easily "zeroed" indicating the lack of temperature gradients and effectiveness of the soil as a heat sink.

Perhaps the largest single unknown in this study concerning psychrometric estimations of water potential in the tree trunk was: what did the water potential measurements really represent? In contrast to the soil, there is much more biological disturbance when psychrometers are implanted in living tissue of a tree. Boring a hole into a tree surely severs all of the conducting elements thereby locally disrupting the transpiration stream. Evidence shown in this study clearly demonstrates that the relative vapor pressure within these cavities changes markedly from hour-to-hour and from day-to-day. One would not expect this to happen if the transpiration stream is broken. The fact that such changes do occur calls for some explanation; and it may well be that water potential in the psychrometer chamber was not dependent upon water potential of the transpiration stream in the immediate surrounding wood, but upon water potential some distance away where conducting elements were not damaged.

One problem with implanting psychrometers in conifers is that their useful lives are shortened by flowing resin. Toward the end of the summer of 1971, many of the units of this study ceased to function; and when they were removed from the tree, they were inevitably filled with a thick, resinous material. In mature Engelmann spruce, a three month life expectancy is the maximum that can be expected. One would be advised to install new psychrometers approximately every two months if a long period study were planned. The symptom of a resin-fouled psychrometer is a low and constant output at all times. Evidently when the psychrometer chamber has been sealed with resin, water vapor is no longer free to move in or out, and readings stabilize at a value depending upon the amount of water trapped in the chamber and the water potential of the surrounding resin. If resin covers the wet-bulb junction itself, the cooling properties of the wet-bulb junction are destroyed and the psychrometer will not function at all.

Pressure chamber

A similar problem exists with pressure chamber determinations of stem water potential as exists with psychrometric measurements of water potential. It is difficult to ascertain exactly what component potentials are involved. Zimmerman (1971) reviewing data of Scholander et al. (1965) believes that Scholander's daily cycle in pressure chamber measurements is somewhat exaggerated, thus leading to speculation that leaf (or stomatal) resistances are influencing pressures necessary to force sap from the stems. Because of this, xylem water potential (that which is desired to be measured) is confounded and inseparable from other component potentials or resistances in the stem samples.

From this study the value of pressure chamber measurements was shown as (1) ease of measurement, and (2) reduction of experimental error (there is less error in procedure in addition to less inherent sampling variation). A serious drawback of these measurements was the difficulty experienced in obtaining samples. The only way samples could be obtained above two meters was to climb the trees--this is nearly impossible to do without climbing equipment. Some researchers (e.g., Scholander, et al., 1965) have obtained samples by shooting down small branches from the tops of 30 meter or taller trees, but this practice is questionable, as the ends of the samples are frayed and cutting them to obtain a smooth surface results in a potential bias of the readings. There is also the possibility of branches being caught in the tree as they fall to the ground.

An additional problem that occurred during the study with the pressure chamber was sticking of the chamber top to the chamber body when the air temperature dropped below about 10 C. Lanolin compound proved completely unsatisfactory for lubrication purposes and a better lubricant (one less affected by temperature) is needed if the pressure chamber is to be used in cold temperatures. One may want to investigate the possibility of using a silicone lubricant, since its viscosity is much less dependent upon temperature.

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APPENDICES

Appendix A

Soil parameters

Table 14. Soil water content, soil water status and soil temperature by depth and by date of measurement.

Key for Tables 14A, 14B, 14C, 14D, 14E, and 14F

[1]Soil water content determined by the neutron scattering method. These values are not plot means, but rather, are values taken from an access tube in conjunction with each tensiometer and psychrometer stack (see Figure 3 for location). Tubes represented are as follows:

Plot	Tube ID
Spruce 1	B
Spruce 2	F
Spruce 3	I
Spruce 4	L
Meadow 1	D
Meadow 2	U

[2]Soil matric potential as measured by tensiometers in the range 0 to - 0.8 bar and by thermocouple psychrometers in the range - 0.5 bar to - 30.0 bars.

[3]Total soil water potential, a summation of the components:

ψ soil = $\theta + \tau + Z$, where

θ = osmotic potential (assumed negligible)
τ = matric potential
Z = gravitational potential, calculated by $\frac{1022 \text{ cm/bar}}{\text{cm depth}}$, and assuming $\rho_{water} = 1.0 \text{g cm}^{-3}$ and $g = 980 \text{ cm sec}^{-2}$.

The unit volume system was used in all calculations (1 bar = 10^6 dyne cm^{-2})

[4]Soil temperature was measured by two copper-constantan thermocouples at a given depth at each plot; one was placed with each tensiometer/ psychrometer stack, the other was located within the plot at some distance away. Readings were taken between the hours 0900 and 1000 MST throughout the data collection period.

Table 14. Soil water content, soil water status and soil temperature by depth and by date of measurement at Spruce plot 1, 1971.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp.[4] (^oC)
7-03-71	15	0.31			5.2
	30				3.1
	45	0.31			2.9
	75	0.41			
	90				1.8
	105	0.41			
7-13-71	15	0.26	- 0.20	- 0.21	8.4
	30		- 0.16	- 0.19	5.6
	45	0.27	- 0.09	- 0.13	5.9
	75	0.32			
	90		- 0.04	- 0.13	3.5
	105	0.39			
7-20-71	15	0.23	- 0.52	- 0.53	9.0
	30		- 0.28	- 0.31	7.9
	45	0.25	- 0.15	- 0.19	8.1
	75	0.30			
	90		- 0.06	- 0.15	5.3
	105	0.39			
7-28-71	15	0.18	- 0.59	- 0.60	9.2
	30		- 0.41	- 0.44	7.7
	45	0.23	- 0.24	- 0.28	8.3
	75	0.29			
	90		- 0.09	- 0.18	5.9
	105	0.38			
8-10-71	15	0.15	- 3.3	- 3.3	9.8
	30		- 3.1	- 3.1	8.4
	45	0.18	- 2.4	- 2.4	9.0
	75	0.24			
	90		- 0.25	- 0.34	7.1
	105	0.36			
8-25-71	15	0.15	- 6.3	- 6.3	9.5
	30		- 2.2	- 2.2	9.1
	45	0.14	- 2.0	- 2.0	9.9
	75	0.19			
	90		- 0.25	- 0.34	7.7
	105	0.33			

Table 14A Continued.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp.[4] (^oC)
9-07-71	15	0.10	- 7.3	- 7.3	7.5
	30		- 2.2	- 2.2	7.2
	45	0.13	- 2.6	- 2.6	7.3
	75	0.16			
	90		- 0.5	- 0.6	6.5
	105	0.30			
9-22-71	15	0.10	- 8.2	- 8.2	5.2
	30		- 2.0	- 2.0	5.4
	45	0.08	- 2.2	- 2.2	5.2
	75	0.12			
	90		- 1.0	- 1.1	5.4
	105	0.15			

Table 14B. Soil water content, soil water status and soil temperature by depth and by date of measurement at Spruce plot 2, 1971.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp.[4] (°C)
7-03-71	15				8.7
	30				7.7
	45				7.2
	75				
	90				5.0
	105				
7-13-71	15	0.22	- 0.20	- 0.21	9.5
	30		- 0.15	- 0.18	8.7
	45	0.24	- 0.10	- 0.14	8.4
	75	0.32			
	90		- 0.06	- 0.15	5.8
	105	0.39			
7-20-71	15	0.21	- 0.29	- 0.30	10.9
	30		- 0.25	- 0.28	10.5
	45	0.22	- 0.16	- 0.20	10.0
	75	0.32			
	90		- 0.08	- 0.17	7.6
	105	0.38			
7-28-71	15	0.18	- 0.48	- 0.49	11.4
	30		- 0.35	- 0.38	11.0
	45	0.20	- 0.23	- 0.27	10.5
	75	0.32			
	90		- 0.09	- 0.18	8.4
	105	0.38			
8-10-71	15	0.14	- 0.40	- 0.41	12.0
	30		- 2.2	- 2.2	11.3
	45	0.16	- 0.3	- 0.34	11.0
	75	0.27			
	90		- 0.13	- 0.22	8.9
	105	0.36			
8-25-71	15	0.10	- 7.1	- 7.1	11.3
	30		- 2.6	- 2.6	11.0
	45	0.12	- 1.9	- 1.9	10.8
	75	0.22			
	90		- 0.22	- 0.31	9.6
	105	0.34			

Table 14B Continued.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp.[4] (°C)
9-07-71	15	0.11	- 3.3	- 3.3	8.2
	30		- 2.4	- 2.4	8.5
	45	0.11			
	75	0.18			
	90		- 0.43	- 0.52	7.9
	105	0.32			
9-22-71	15	0.11	- 2.7	- 2.7	4.8
	30		- 3.6	- 3.6	5.0
	45	0.10	- 0.6	- 0.64	5.3
	75	0.15			
	90		- 0.56	- 0.65	5.6
	105	0.29			

Table 14C. Soil water content, soil water status, and soil temperature by depth and by date of measurement at Spruce plot 3, 1971.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp.[4] (°C)
7-03-71	15	0.31			5.4
	30				3.4
	45	0.28			3.4
	75	0.24			
	90				1.8
	105	0.26			
7-13-71	15	0.22	- 0.24	- 0.25	9.1
	30		- 0.17	- 0.20	5.6
	45	0.23	- 0.14	- 0.18	4.7
	75	0.20			
	90		- 0.13	- 0.22	3.2
	105	0.19			
7-20-71	15	0.20	- 0.44	- 0.45	10.0
	30		- 0.43	- 0.46	7.6
	45	0.22	- 0.26	- 0.30	6.8
	75	0.20			
	90		- 0.06	- 0.15	5.2
	105	0.20			
7-28-71	15	0.16	- 0.59	- 0.60	10.3
	30		- 0.61	- 0.64	8.3
	45	0.18	- 0.49	- 0.53	7.2
	75	0.19			
	90		- 0.08	- 0.17	5.7
	105	0.19			
8-10-71	15	0.11	- 2.8	- 2.8	10.8
	30		- 0.10	- 0.13	8.6
	45	0.13	- 0.58	- 0.62	7.7
	75	0.16			
	90		- 0.15	- 0.24	6.2
	105	0.17			
8-25-71	15	0.09	- 5.5	- 5.5	10.3
	30		- 4.4	- 4.4	9.0
	45	0.11	- 3.6	- 3.6	8.4
	75	0.12			
	90		- 0.37	- 0.46	7.1
	105	0.15			

Table 14C Continued.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp.[4] (^oC)
9-07-71	15	0.10	- 0.5	- 0.5	7.2
	30		- 3.4	- 3.4	7.1
	45	0.10	- 4.8	- 4.8	7.0
	75	0.11			
	90		- 0.53	- 0.62	6.5
	105	0.12			
9-22-71	15	0.09	- 3.2	- 3.2	4.4
	30		- 5.3	- 5.3	4.5
	45	0.10	- 5.6	- 5.6	4.5
	75	0.10			
	90		- 0.7	- 0.8	4.9
	105	0.10			

Table 14D. Soil water content, soil water status, and soil temperature by depth and by date of measurement at Spruce plot 4, 1971.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp.[4] (°C)
7-03-71	15				3.9
	30				3.1
	45				2.9
	75				
	90				1.8
	105				
7-13-71	15		- 0.15[a]	- 0.16[a]	6.2
	30		- 0.08	- 0.11	5.2
	45		- 0.09	- 0.13	4.5
	75				
	90		- 0.05	- 0.14	3.1
	105				
7-20-71	15	0.17	- 1.3[a]	- 1.3[a]	7.9
	30		- 0.19	- 0.22	7.1
	45	0.21	- 0.22	- 0.26	7.0
	75	0.27			
	90		- 0.07	- 0.16	5.2
	105	0.39			
7-28-71	15	0.13	- 2.4[a]	- 2.4[a]	8.3
	30		- 0.34	- 0.32	7.7
	45	0.17	- 0.41	- 0.45	7.3
	75	0.24			
	90		- 0.08	- 0.17	5.8
	105	0.36			
8-10-71	15	0.10	- 3.8	- 3.8	9.1
	30		- 0.60	- 0.63	8.7
	45	0.14	- 0.62	- 0.66	7.9
	75	0.23			
	90		- 0.14	- 0.23	6.6
	105	0.39			
8-25-71	15	0.08	- 3.1	- 3.1	9.0
	30		- 1.7	- 1.7	8.5
	45	0.10	- 2.3	- 2.3	8.2
	75	0.19			
	90		- 0.32	- 0.41	7.2
	105	0.35			

Table 14D Continued.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp.[4] (°C)
9-07-71	15	0.12	- 2.4	- 2.4	7.1
	30		- 0.5	- 0.5	7.1
	45	0.12	- 3.0	- 3.0	6.8
	75	0.18			
	90		- 0.32	- 0.41	6.6
	105	0.30			
9-22-71	15	0.09	- 4.6	- 4.6	4.8
	30		- 2.7	- 2.7	5.2
	45	0.10	- 3.3	- 3.3	5.0
	75	0.15			
	90		- 0.32	- 0.41	5.0
	105	0.25			

[a]Estimated value.

Table 14E. Soil water content, soil water status, and soil temperature by depth and by date of measurement at Meadow plot 1, 1971.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp.[4] (°C)
7-03-71	5				
	15	0.26	- 0.20	- 0.21	10.1
	30		- 0.11	- 0.14	10.5
	45	0.33	- 0.07	- 0.11	10.1
	75	0.37			
	90		- 0.07	- 0.16	6.3
	105	0.44			
7-12-71	5				
	15	0.18	- 0.57	- 0.58	14.2
	30		- 0.26	- 0.29	13.4
	45	0.32	- 0.10	- 0.14	13.1
	75	0.36			
	90		- 0.08	- 0.17	8.9
	105	0.43			
7-19-71	5				
	15	0.13			14.8
	30		- 0.46	- 0.49	14.9
	45	0.30	- 0.13	- 0.17	14.9
	75	0.34			
	90		- 0.08	- 0.17	11.9
	105	0.42			
7-26-71	5				
	15	0.12			13.9
	30		- 0.58	- 0.61	14.6
	45	0.29	- 0.15	- 0.19	15.0
	75	0.33			
	90		- 0.09	- 0.18	11.4
	105	0.43			
8-09-71	5		- 0.10	- 0.10	14.3[a]
	15	0.15	- 0.60	- 0.61	13.8
	30		- 2.0	- 2.0	14.8
	45	0.25	- 0.24	- 0.28	14.8
	75	0.32			
	90		- 0.10	- 0.19	12.6
	105	0.42			

Table 14E Continued.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp.[4] (°C)
8-23-71	5		- 9.2	- 9.2	15.3[a]
	15	0.07	- 0.7	- 0.7	16.1
	30		- 2.8	- 2.8	16.3
	45	0.21	- 0.32[b]	- 0.36[b]	15.9
	75	0.30			
	90		- 0.10	- 0.19	13.8
	105	0.41			
9-06-71	5		- 2.0[b]	- 2.0[b]	10.8[a]
	15	0.11	- 2.7	- 2.7	11.0
	30		- 3.1	- 3.1	11.8
	45	0.16	- 0.45[b]	- 0.49[b]	11.9
	75	0.28			
	90		- 0.13	- 0.22	11.5
	105	0.39			
9-20-71	5				5.4
	15	0.11	- 0.5	- 0.5	6.5
	30		- 4.5	- 4.5	8.2
	45	0.20	- 0.37	- 0.41	8.5
	75	0.28			
	90		- 0.12[b]	- 0.21[b]	8.7
	105	0.31			

[a]As measured by a copper-constantan thermocouple embedded in psychrometer unit.
[b]Estimated value.

Table 14F. Soil water content, soil water status, and soil temperature by depth and by date of measurement at Meadow plot 2, 1971.

Date of meas.	Depth (cm)	θ[1] (cm^3/cm^3)	Soil τ[2] (bars)	Soil ψ[3] (bars)	Soil temp. (^oC)
7-03-71	5				
	15	0.29	- 0.13	- 0.14	9.4
	30		- 0.07	- 0.10	10.1
	45	0.31	- 0.05	- 0.09	8.5
	75	0.40			
	90		- 0.00	- 0.09	6.6
	105	0.49			
7-12-71	5				
	15	0.21	- 0.43	- 0.44	13.3
	30		- 0.13	- 0.16	12.3
	45	0.26	- 0.08	- 0.12	11.9
	75	0.30			
	90		- 0.02	- 0.11	8.7
	105	0.44			
7-19-71	5				
	15	0.19	- 0.58	- 0.59	14.8
	30		- 0.20	- 0.23	14.1
	45	0.27	- 0.10	- 0.14	14.4
	75	0.31			
	90		- 0.03	- 0.12	11.0
	105	0.46			
7-26-71	5				
	15	0.16			
	30		- 0.25	- 0.28	14.0
	45	0.25	- 0.11	- 0.15	14.3
	75	0.30			
	90		- 0.03	- 0.12	11.8
	105	0.44			
8-09-71	5		- 2.5	- 2.5	14.3[b]
	15	0.14	- 1.5	- 1.5	13.9
	30		- 0.40	- 0.43	14.2
	45	0.24	- 0.13	- 0.17	14.4
	75	0.30			
	90		- 0.04	- 0.13	12.0
	105	0.44			

Table 14F Continued.

Date of meas.	Depth (cm)	[1] (cm^3/cm^3)	Soil [2] (bars)	Soil [3] (bars)	Soil temp.[4] (°C)
8-23-71	5		- 16.5	- 16.5	15.8[b]
	15	0.10	- 2.1	- 2.1	15.8
	30		- 0.7	- 0.7	15.6
	45	0.22	- 0.17	- 0.21	15.2
	75	0.28			
	90		- 0.05	- 0.14	13.1
	105	0.41			
9-06-71	5		- 1.2	- 1.2	11.0[b]
	15	0.10	- 2.0	- 2.0	11.5
	30		- 2.0	- 2.0	11.7
	45	0.25	- 0.18	- 0.22	11.7
	75	0.29			
	90		- 0.07	- 0.16	11.2
	105	0.35			
9-20-71	5		- 0.1	- 0.1	10.1[b]
	15	0.12			9.2
	30		- 2.1	- 2.1	9.4
	45	0.21	- 0.24	- 0.26	10.2
	75	0.24			
	90		- 0.09	- 0.18	9.6
	105	0.36			

[b]As measured by copper-constantan thermocouple embedded in psychrometer unit.

Table 15. Mean soil water content as it varied by depth and by date for the 1970 study period. Soil water content was estimated by use of neutron scattering equipment.[a]

Spruce plot 1. N= 25

Depth (cm)	Date of measurement							
	7-03	7-10	7-17	7-24	7-31	8-07	8-21	9-04
15	0.22	0.19	0.15	0.13	0.12	0.11	0.09	0.08
45	0.29	0.26	0.25	0.22	0.20	0.18	0.15	0.14
75	0.36	0.35	0.33	0.31	0.29	0.27	0.23	0.21
105	0.39	0.38	0.38	0.36	0.35	0.34	0.31	0.29

Meadow plot 1. N=28

Depth (cm)	Date of measurement							
	7-02	7-09	7-16	7-23	7-30	8-06	8-20	9-03
15	0.23	0.16	0.15	0.10	0.09	0.08	0.05	0.06
45	0.34	0.31	0.31	0.29	0.27	0.26	0.21	0.20
75	0.39	0.37	0.36	0.34	0.34	0.33	0.31	0.31
105	0.43	0.42	0.42	0.40	0.39	0.39	0.38	0.37

[a] θ, expressed as cm^3/cm^3

Table 16. Mean soil water content as it varied by depth and by date for the 1971 study period. Soil water content was estimated by use of neutron scattering equipment.

Spruce plot 1. N = 5

Depth (cm)	Date of measurement							
	7-03	7-13	7-20	7-28	8-10	8-24	9-07	9-20
15	0.32	0.26	0.20	0.15	0.12	0.10	0.11	0.09
45	0.33	0.29	0.27	0.25	0.19	0.15	0.14	0.13
75	0.40	0.37	0.35	0.34	0.29	0.25	0.22	0.21
105	0.41	0.40	0.39	0.39	0.37	0.34	0.33	0.29

Spruce plot 2. N = 6

Depth (cm)	Date of measurement							
	7-03	7-13	7-20	7-28	8-10	8-25	9-07	9-22
15	0.29	0.23	0.20	0.17	0.16	0.11	0.15	0.13
45	0.32	0.28	0.26	0.24	0.20	0.17	0.15	0.14
75	0.36	0.34	0.33	0.31	0.28	0.24	0.21	0.19
105	0.41	0.39	0.38	0.37	0.35	0.33	0.30	0.28

Spruce plot 3. N = 5

Depth (cm)	Date of measurement							
	7-03	7-13	7-20	7-28	8-10	8-25	9-07	9-22
15	0.30	0.23	0.20	0.16	0.12	0.08	0.15	0.09
45	0.33	0.30	0.27	0.25	0.20	0.15	0.16	0.14
75	0.36	0.35	0.34	0.33	0.30	0.26	0.24	0.21
105	0.38	0.35	0.34	0.33	0.31	0.28	0.26	0.24

Table 16. Continued.

Spruce plot 4. N = 3

Depth (cm)	Date of measurement							
	7-03	7-15	7-20	7-28	8-10	8-25	9-07	9-22
15	0.29	0.25	0.21	0.18	0.14	0.10	0.13	0.10
45	0.30	0.28	0.25	0.22	0.20	0.16	0.15	0.13
75	0.29	0.27	0.27	0.26	0.24	0.21	0.20	0.18
105	0.43	0.41	0.40	0.39	0.39	0.36	0.33	0.30

Meadow plot 1. N = 4

Depth (cm)	Date of measurement							
	7-03	7-12	7-19	7-26	8-09	8-23	9-06	9-20
15	0.25	0.19	0.16	0.13	0.15	0.10	0.12	0.12
45	0.34	0.32	0.30	0.29	0.26	0.25	0.22	0.23
75	0.38	0.35	0.34	0.33	0.32	0.31	0.29	0.29
105	0.44	0.41	0.40	0.37	0.38	0.37	0.35	0.33

Meadow plot 2. N = 5

Depth (cm)	Date of measurement							
	7-03	7-12	7-19	7-26	8-09	8-23	9-06	9-20
15	0.30	0.21	0.21	0.17	0.15	0.11	0.13	0.13
45	0.30	0.26	0.28	0.27	0.26	0.24	0.23	0.22
75	0.38	0.30	0.33	0.30	0.31	0.29	0.29	0.27
105	0.50	0.42	0.46	0.44	0.44	0.40	0.38	0.37

[a] θ, expressed as cm^3/cm^3

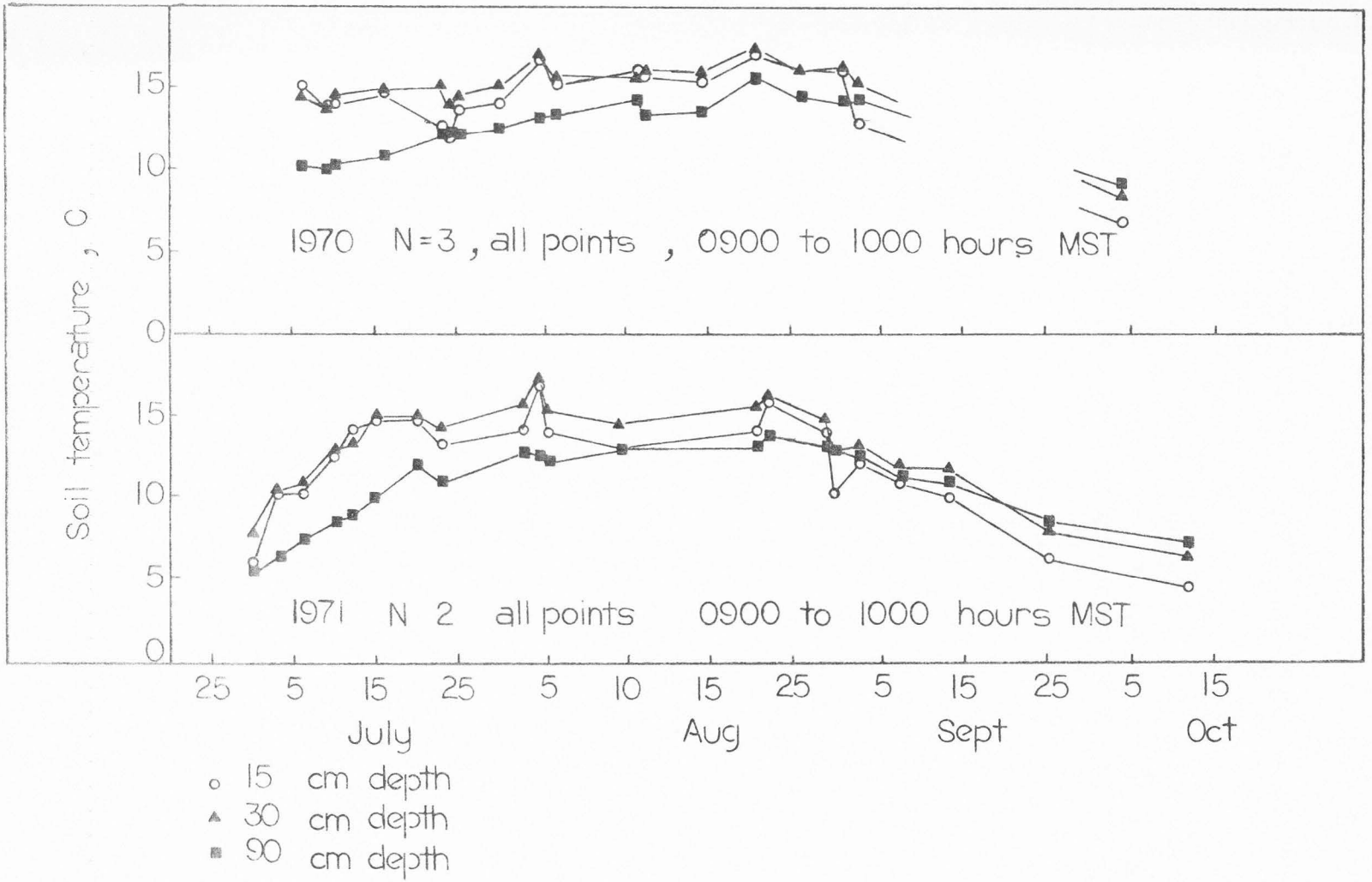


Figure 22. A comparison of soil temperature between the summer months of 1970 and 1971 at meadow plot 1.

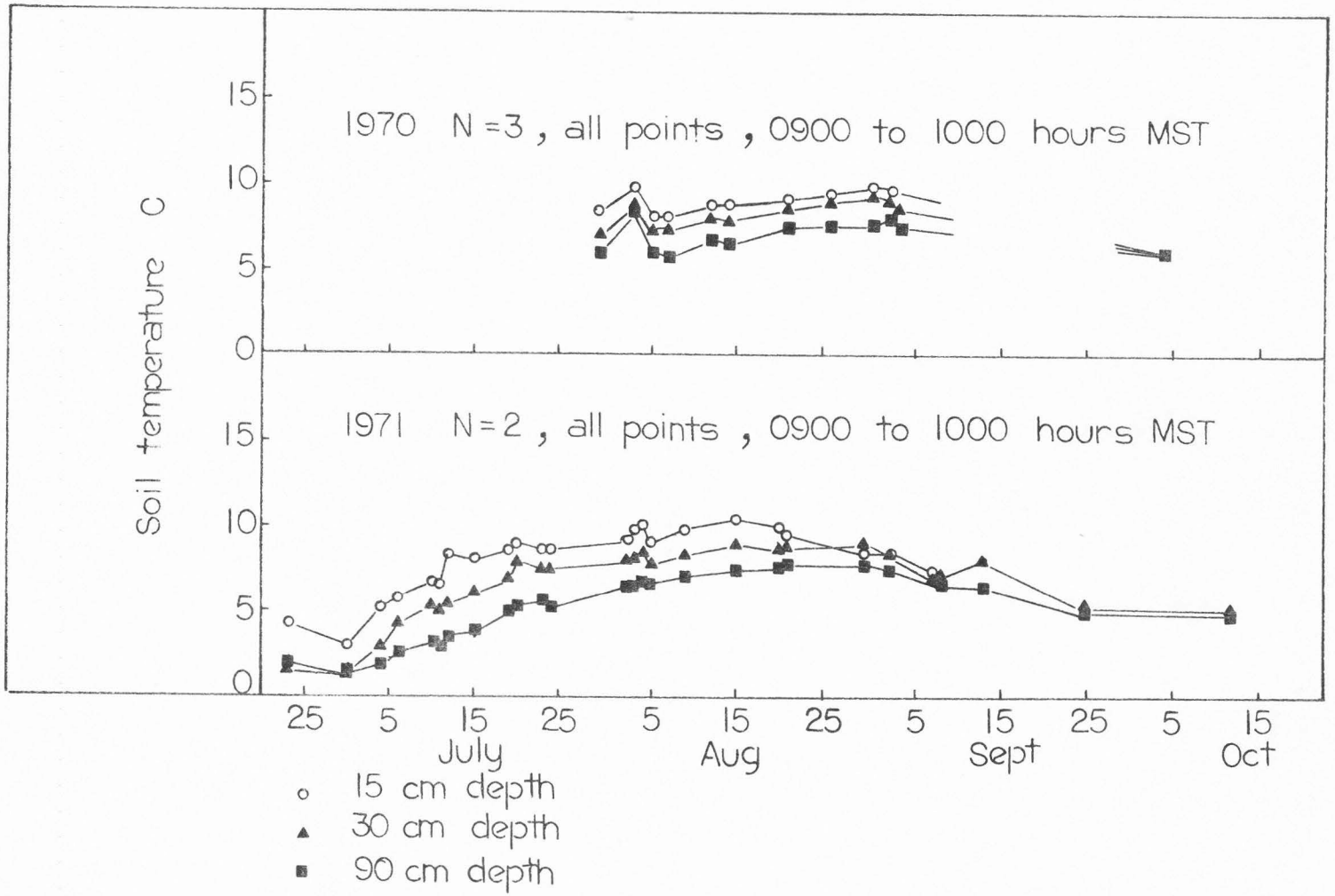


Figure 23. A comparison of soil temperature between the summer months of 1970 and 1971 at spruce plot 1.

Appendix B

Trunk and stem water potential and selected environmental factors

Table 17. Diurnal measurements of trunk water potential, global radiation, wind, and vapor pressure deficit during the 1971 study period.

Date	Time (t)	ψ_T[1] (bars)	$s_{\bar{x}}$ (T) (bars)	ψ_S[2] (bars)	$s_{\bar{x}}$ (S) (bars)	R_G (t-2hrs)[3] (ly min^{-1})	Wind (t-1hr)[4] (mph)	Vpd (t-24hrs)[5] (bars)	Vpd (t)[5] (bars)
7-11-71	0300	- 3.6	-0.3			0.00	0.0	10.8	8.4
	0600	- 3.3	-0.4			0.00	0.0	10.8	7.9
	0900	- 7.1	-2.5			0.10	1.3	10.4	9.5
	1200	-18.3	-6.8			1.25	3.0	13.8	12.5
	1500	-31.5	-9.1			1.50	4.6	13.9	13.9
	1650	-20.0	-5.4			1.20	5.3	13.4	13.5
	1800	-14.5	-4.2			1.05	3.3	13.3	13.2
	2100	- 4.1	-0.6			0.05	1.7	10.7	10.4
7-19-71	0600	- 3.9	-1.5			0.00	0.0	4.9	0.2
	0900	- 2.1	-1.0			0.20	0.3	4.8	1.2
	1000	- 0.9	-0.4			0.55	8.0	5.7	2.0
	1100	- 1.6	-0.5			0.40	4.0	6.9	2.8
	1200	- 3.1	-0.6			0.75	4.0	8.2	3.7
	1300	- 1.7	-0.8			0.45	3.0	4.6	4.8
	1400	- 2.9	-0.6			0.95	3.0	0.9	6.0
	1500	- 2.1	-1.0			0.20	3.0	2.1	6.3
	1800	- 2.5	-1.0			0.30	0.3	0.0	5.4
7-24-71	0600	- 1.9	-0.4	-12.0	-0.6	0.00	0.0	1.4	3.6
	0900	- 4.3	-2.0			0.05	0.6	3.5	5.6
	1000	- 7.4	-3.6			0.15	3.0	4.6	7.0
	1100	-14.5	-5.8			0.25	4.0	4.6	10.1
	1200	-24.1	-7.5	-18.2	-0.5	0.80	2.0	4.7	13.2
	1400	-29.2	-9.5			1.25	3.0	8.4	14.8
	1500	-28.9	-9.4			1.05	3.0	7.9	12.7
	1600	-10.8	-2.7			0.95	4.0	7.5	10.6
	1800	- 8.9	-2.7	- 9.1	-0.5	0.60	2.0	6.5	10.1
	2100	- 3.6	-1.1			0.25	3.0	5.0	8.9

Table 17. Continued.

Date	Time (t)	ψ_T[1] (bars)	$s_{\bar{x}}$ (T) (bars)	ψ_S[2] (bars)	$s_{\bar{x}}$ (S) (bars)	R_G (t-2hrs)[3] (ly min^{-1})	Wind (t-1hr)[4] (mph)	Vpd (t-24hrs)[5] (bars)	Vpd (t)[5] (bars)
8-03-71	0600	- 2.1	-0.5			0.00	0.0	10.1	9.7
	0900	-11.4	-4.0			0.20	1.0	11.1	11.7
	1000	-15.8	-5.8			0.95	2.0	13.5	12.8
	1100	-23.5	-9.4			1.10	2.0	15.2	14.7
	1300	-32.6	-9.6			1.45	2.5	18.5	16.9
	1400	-28.6	-8.6			1.45	4.0	20.1	17.3
	1500	-29.4	-8.6			1.20	3.0	19.0	16.7
	1800	-10.4	-2.8			0.45	1.6	14.7	11.8
	2100	- 3.9	-1.0			0.00	1.0	11.6	9.8
8-10-71	0700	- 2.8	-0.2	-12.6	-0.5	0.00	0.0	4.8	11.7
	0900	-16.9	-4.9			0.15	0.6	6.5	13.6
	1000	-25.1	-8.8			1.00	2.0	8.0	15.3
	1200	-31.9	-9.9	-14.7	-0.5	1.30	2.0	13.7	17.7
	1300	-32.8	-9.6			1.40	2.0	15.6	18.7
	1400	-33.0	-10.0			1.40	2.0	17.5	19.7
	1500	-37.1	-10.3	-12.1	-0.6	1.25	2.0	17.9	19.3
	1600	-28.3	-8.5			1.15	2.0	18.4	18.9
	1800	-11.2	-2.1	- 9.2	-0.3	0.70	2.5	16.9	15.3
	2100	- 3.0	-0.2	- 7.8	-0.3	0.00	0.6	13.4	11.3
9-08-71	0700	- 1.6	-0.6			0.00	1.0	0.1	6.3
	0900	- 2.4	-0.2	-10.1	-0.6	0.05	1.0	1.1	7.2
	1000	- 2.0	-0.5			0.25	2.0	2.3	7.9
	1100	- 2.8	-0.3			1.05	1.5	3.0	9.4
	1300	- 3.8	-1.8	-16.6	-0.4	1.25	2.5	5.5	11.3
	1500	- 4.0	-2.1	-15.8	-0.8	1.25	2.5	8.2	11.5
	1700	- 2.9	-1.3			0.95	2.0	8.3	10.4
	1900	- 2.2	-0.5	-10.8	-0.7	0.25	0.5	6.4	8.7

Table 17. Continued.

Date	Time (t)	ψ_T[1] (bars)	$s_{\bar{x}}$ (T) (bars)	ψ_S[2] (bars)	$s_{\bar{x}}$ (S) (bars)	R_G (t-2hrs)[3] (ly min^{-1})	Wind (t-1hr)[4] (mph)	Vpd (t-24hrs)[5] (bars)	Vpd (t) (bars)
9-24-71	0600	- 2.0	-0.7			0.00	3.0	5.3	6.8
	0900	- 6.2	-1.4	-18.0	-1.2	0.05	2.5	8.0	7.5
	1100	-13.9	-3.1			0.80	4.0	10.5	9.3
	1300	-23.7	-12.3	-16.6	-1.2	1.15	5.0	14.0	10.3
	1500	-14.9	-6.0			1.20	4.5	14.0	10.9
	1800	- 6.4	-1.4	-14.0	-0.5	0.70	2.0	8.2	9.5
	2200	- 3.3	-0.3			0.00	2.0	7.2	8.1

[1]Water potential as measured by the mean of 6 Spanner thermocouple psychrometers, each placed in the outer xylem of an individual tree about 1.0 meter above the ground.

[2]Water potential of spruce stems (last 3 year's growth) as determined by a pressure bomb. Samples were taken from the north side of trees at 1 to 2 meters height.

[3]Instantaneous incoming global radiation as measured by a bimetallic actinograph.

[4]Mean wind which occurred in the 1 hour period preceding a measurement, measured by a totalizing anemometer at 9.5 meters above the ground at the Tower weather station.

[5]Vapor pressure deficit of the air was estimated by the formula:

Vpd = Vps (1 - Rh/100) where
Vps is the saturated vapor pressure of the air at ambient air temperature. Both air temperature and relative humidity for this parameter were obtained from a hygrothermograph located at B-station in the spruce stand.

Table 18. Seasonal measurement of trunk and stem water potentials and selected soil and atmospheric factors during the 1971 study period. Dates selected are those in which three or more of the plots were monitored.

Date	Plot	Time (t)	ψ_S[1] (t+1hr) (bars)	ψ_T[2] (t) (bars)	Wind[3] (miles)	G[4] (t-2hrs) ($lymin^{-1}$)	Vpd (t) (mb)	Vpd (t-24hrs) (mb)	Soil[5] τ (bars)	Soil[6] temp. (^oC)	Soil[7] water (cm/120cm)
7-04-71	1	0930		- 3.1		0.30			0.00	5.2	44.0
	2								0.00	5.2	42.0
	3	1000		- 3.1		0.60			0.00	5.4	41.5
	4	1015		- 2.9		0.55			0.00	3.9	40.5
	Mean	1000		- 3.0	2.2	0.48	5.15	6.86	0.00	4.9	42.0
	$s_{\bar{X}}$			- 0.1							
7-06-71	1	0900		-14.0		0.10			-0.06	5.9	
	2	0930		-13.9		0.30			-0.09	8.7	
	3	1000		-15.4		0.90			-0.05	5.4	
	4	1030		- 0.5		1.00			0.00	4.9	
	Mean	1000		-13.3	1.8	0.57	9.99	8.72	-0.05	6.2	
	$s_{\bar{X}}$			- 3.3							
7-10-71	1	0900		- 6.9		0.10			-0.10	6.8	
	2	1130		-18.6		1.15			-0.11	9.3	
	3	1130		-27.3		1.15			-0.09	8.5	
	4	1030		- 6.1		0.95			-0.05	6.1	
	Mean	1100		-14.7	2.9	0.84	12.42	11.84	-0.09	7.7	
	$s_{\bar{X}}$			- 4.4							
7-11-71	1	1200		-17.8		1.25			-0.11	7.0	
	2	1215		-18.0		1.35			-0.12	9.4	
	3								-0.11	8.8	
	4	1300		-20.9		1.40			-0.07	6.1	
	Mean	1200		-18.9	1.3	1.33	12.57	13.75	-0.10	7.8	
	$s_{\bar{X}}$			- 5.8							

Table 18. Continued.

Date	Plot	Time (t)	ψ_S[1] (t+1hr) (bars)	ψ_T[2] (t) (bars)	Wind[3] (miles)	R_G[4] (t-2hrs) ($lymin^{-1}$)	Vpd (t) (mb)	Vpd (t-24hrs) (mb)	Soil[5] τ (bars)	Soil[6] temp. (^oC)	Soil[7] water (cm/120cm)
7-12-71	1	1000		-10.0		0.50			-0.12	8.4	40.5
	2	1000		-18.1		0.50			-0.13	9.5	38.0
	3	1230		-45.7		1.30			-0.14	9.1	37.5
	4								-0.09	6.2	36.5
	Mean	1100		-24.6	0.5	0.77	13.84	11.54	-0.12	8.3	38.1
	$s_{\bar{X}}$			- 7.1							
7-15-71	1	1000		-12.1		0.50			-0.17	8.1	
	2	1000		-26.1		0.50			-0.16	8.7	
	3	1015		-23.7		0.90			-0.21	8.7	
	4	1030		- 6.1		0.90			-0.15	7.1	
	Mean	1000		-17.0	1.3	0.70	14.65	12.52	-0.17	8.1	
	$s_{\bar{X}}$			- 4.4							
7-20-71	1	1000		- 3.2		0.55			-0.25	9.0	37.0
	2	1000		- 7.4		0.55			-0.20	11.0	35.5
	3	1015		-27.2		0.85			-0.30	10.0	35.0
	4	1030		- 2.7		0.90			-0.45	7.9	34.5
	Mean	1000		-10.1	1.4	0.71	5.80	1.98	-0.30	9.5	35.5
	$s_{\bar{X}}$			- 4.7							
7-23-71	1	1000	-18.9	- 1.1		0.15			-0.28	8.6	
	2	1000	-17.5	- 3.2		0.15			-0.24	11.2	
	3	1015		- 1.2		0.25			-0.38	9.6	
	4	1030		- 2.1		0.25			-0.51	8.1	
	Mean	1000	-18.2	- 1.8	0.8	0.20	4.57	6.58	-0.35	9.4	
	$s_{\bar{X}}$		- 0.6	- 0.5							

Table 18. Continued.

Date	Plot	Time (t)	ψ_S[1] (t+1hr) (bars)	ψ_T[2] (t) (bars)	Wind[3] (miles)	R_G[4] (t-2hrs) ($lymin^{-1}$)	Vpd (t) (mb)	Vpd (t-24hrs) (mb)	Soil[5] τ (bars)	Soil[6] temp. (^oC)	Soil[7] water (cm/120cm)
8-02-71	1	1000	-14.5	- 8.9		0.95			-1.1	9.1	
	2	1015	-15.9	-16.6		0.95			-0.8	12.3	
	3	1045		-40.8		1.15			-1.3	11.0	
	4	1100		-20.7		1.15			-1.2	8.6	
	Mean	1000	-15.3	-22.2	1.0	1.05	13.48	10.52	-1.1	10.2	
	$s_{\bar{X}}$		- 0.5	- 6.9							
8-09-71	1	1000	-14.8	- 1.8		0.75			-2.3	9.8	29.5
	2	1015	-17.2	-17.1		0.75			-0.8	12.0	30.0
	3	1015	-15.1	-25.2		0.75			-1.1	12.3	31.0
	4	1100	-15.9	-13.1		0.95			-1.3	9.1	29.5
	Mean	1000	-15.7	-14.0	1.4	0.80	7.95	7.87	-1.4	10.8	30.0
	$s_{\bar{X}}$		- 0.5	- 4.1							
8-16-71	1	1000	-17.6	- 1.8		0.55			-2.3	10.3	
	2	1015	-20.4	- 4.4		0.55			-1.7	12.6	
	3	1100	-16.4	- 9.2		1.00			-2.3	12.6	
	4	1115	-19.8	- 5.3		1.00			-2.2	9.5	
	Mean	1000	-18.6	- 5.3	0.6	0.77	10.43	13.36	-2.1	11.2	
	$s_{\bar{X}}$		- 0.8	- 1.2							
8-20-71	1	0930	-16.1	- 2.8		0.10			-2.6	9.9	
	2	1000	-18.5	-15.2		0.50			-1.7	12.2	
	3	1015	-18.5	-23.0		0.50			-2.7	9.5	
	4	1030	-18.3	-10.8		0.90			-2.3	9.3	
	Mean	1000	-17.9	-12.7	1.5	0.50	13.55	11.71	-2.3	10.2	
	$s_{\bar{X}}$		- 0.5	- 3.8							

Table 18. Continued.

Date	Plot	Time (t)	ψ_S[1] (t+1hr) (bars)	ψ_T[2] (t) (bars)	Wind[3] (miles)	R_G[4] (t-2hrs) ($lymin^{-1}$)	Vpd (t) (mb)	Vpd (t-24hrs) (mb)	Soil[5] τ (bars)	Soil[6] temp. (^oC)	Soil[7] water (cm/120cm)
8-22-71	1	1000		- 2.3		0.50			- 2.7	9.5	25.5
	2	1030		-18.3		0.65			- 3.0	12.8	26.0
	3	1330		-46.1		1.25			- 3.5	10.3	23.5
	4	1330		- 8.8		1.25			- 2.6	9.0	25.5
	Mean	1100		-18.9	1.1	0.91	10.45	12.10	- 2.9	10.4	25.1
	$s_{\bar{X}}$			- 7.8							
8-30-71	1	0930	-13.6	- 1.7		0.15			- 3.1	8.5	
	2	1000	-13.2	- 3.1		0.40			- 2.1	9.8	
	3	1030	-12.7	- 1.2		0.90			- 2.8	8.7	
	4	1100	-13.8	- 3.1		1.20			- 1.7	8.6	
	Mean	1000	-13.4	- 2.2	2.1	0.66	5.97	0.37	- 2.4	8.9	
	$s_{\bar{X}}$		- 0.3	- 0.5							
9-02-71	1	1015	-19.9	- 3.6		0.45			- 3.1	8.7	
	2	1030	-16.9	- 8.2		0.75			- 1.3	9.8	
	3	1045	-16.5	-11.8		1.05			- 3.6	8.7	
	4	1100	-18.3	- 6.2		1.05			- 3.2	8.6	
	Mean	1000	-17.9	- 7.4	4.0	0.82	12.13	10.87	- 2.8	8.9	
	$s_{\bar{X}}$		- 0.7	- 1.8							
9-07-71	1	1015	-12.5	- 1.8		0.45			- 3.1	7.5	24.0
	2	1100	-10.9	- 2.1		0.65			- 1.6	8.2	25.0
	3	1130	-10.8	- 2.1		0.75			- 2.3	7.2	25.0
	4	1145	-11.0	- 2.4		0.80			- 1.5	7.1	25.0
	Mean	1100	-11.3	- 2.1	1.8	0.66	3.00	1.69	- 2.1	7.5	24.8
	$s_{\bar{X}}$		- 0.6	- 0.4							

Table 18. Continued.

Date	Plot	Time (t)	ψ_S[1] (t+1hr) (bars)	ψ_T[2] (t) (bars)	Wind[3] (miles)	R_G[4] (t-2hrs) ($lymin^{-1}$)	Vpd (t) (mb)	Vpd (t-24hrs) (mb)	Soil[5] τ (bars)	Soil[6] temp. (°C)	Soil[7] water (cm/120cm)
9-13-71	1	1015	-20.9	- 3.0		0.25			- 3.0	8.2	
	2	1030	-20.4	-16.5		0.35			- 1.8	9.3	
	3	1045	-21.6	- 9.2		0.90			- 3.5	8.2	
	4	1100	-21.5	- 9.2		0.90			- 1.3	8.1	
	Mean	1000	-21.1	- 8.1	2.5	0.60	7.68	11.76	- 2.4	8.4	
	$s_{\bar{x}}$		- 0.4	- 1.7							
9-25-71	1	1000	-17.6	- 2.0		0.10			- 3.3	5.2	22.0
	2	1030	-16.5	- 8.0		0.45			- 1.9	4.8	22.5
	3	1045	-18.1	- 8.7		0.80			- 3.7	4.4	20.5
	4	1100	-18.2	- 5.4		0.80			- 2.7	4.8	22.0
	Mean	1000	-17.5	- 5.7	3.6	0.53	8.09	8.09	- 2.9	4.8	21.7
	$s_{\bar{x}}$		- 0.5	- 1.6							
10-12-71	1	1030		- 0.5		0.70			- 0.3	5.2	
	2	1100		- 2.3		0.85			- 0.7	4.4	
	3	1130		- 1.8		0.85			- 1.2	4.1	
	4	1200		- 3.4		0.95			- 1.2	4.9	
	Mean	1100		- 1.9	1.8	0.84	6.54	8.01	- 0.9	4.6	
	$s_{\bar{x}}$			- 0.4							

[1]Water potential of spruce stems (last 3 year's growth) taken from the north side of trees on each plot at a height of one to two meters. Pressure bomb determinations made.

[2]Trunk water potential at 1 meter height in outer xylem of trees at each plot (mean of 3 thermocouple psychrometers at each plot).

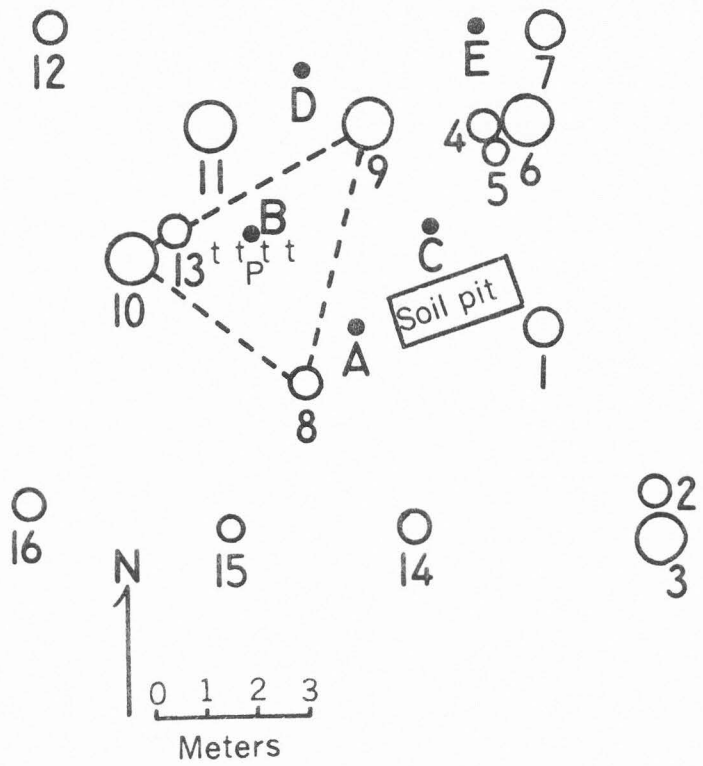
[3]Mean wind speed (mph) on day of measurement.

Table 18. Continued.

[4]Total incoming global radiation as measured by bimetallic actinograph.
[5]Soil matric potential measured by tensiometers in range 0 bar to - 0.8 bar and by thermocouple psychrometers in range 0.5 bar to - 4.0 bar.
[6]Soil temperature at 15 cm depth measured by two temperature thermocouples at each of the respective plots.
[7]Soil water content at each of the plots as estimated by the neutron scattering method.

Appendix C

Plot diagrams and stand data



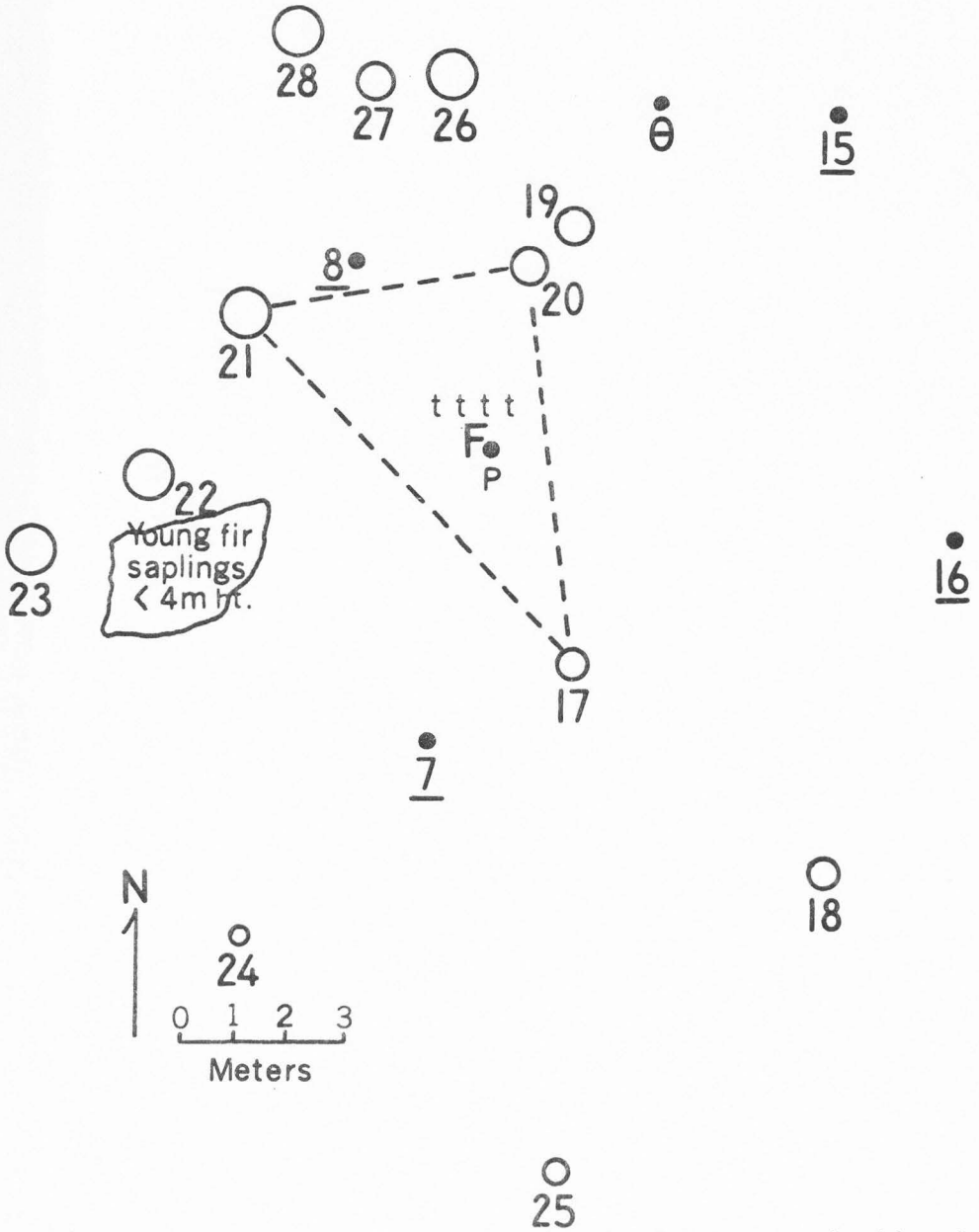
● Neutron probe access tubes with alphabetic identification

t Tensiometer

P Soil psychrometer stack at various depths in the soil

◯ Tree with a numeric identification code. Scale is approximately times two. Trees in which thermocouple psychrometers were implaced are connected with a dotted line.

Figure 24. Location of instrumentation and trees at spruce plot 1.



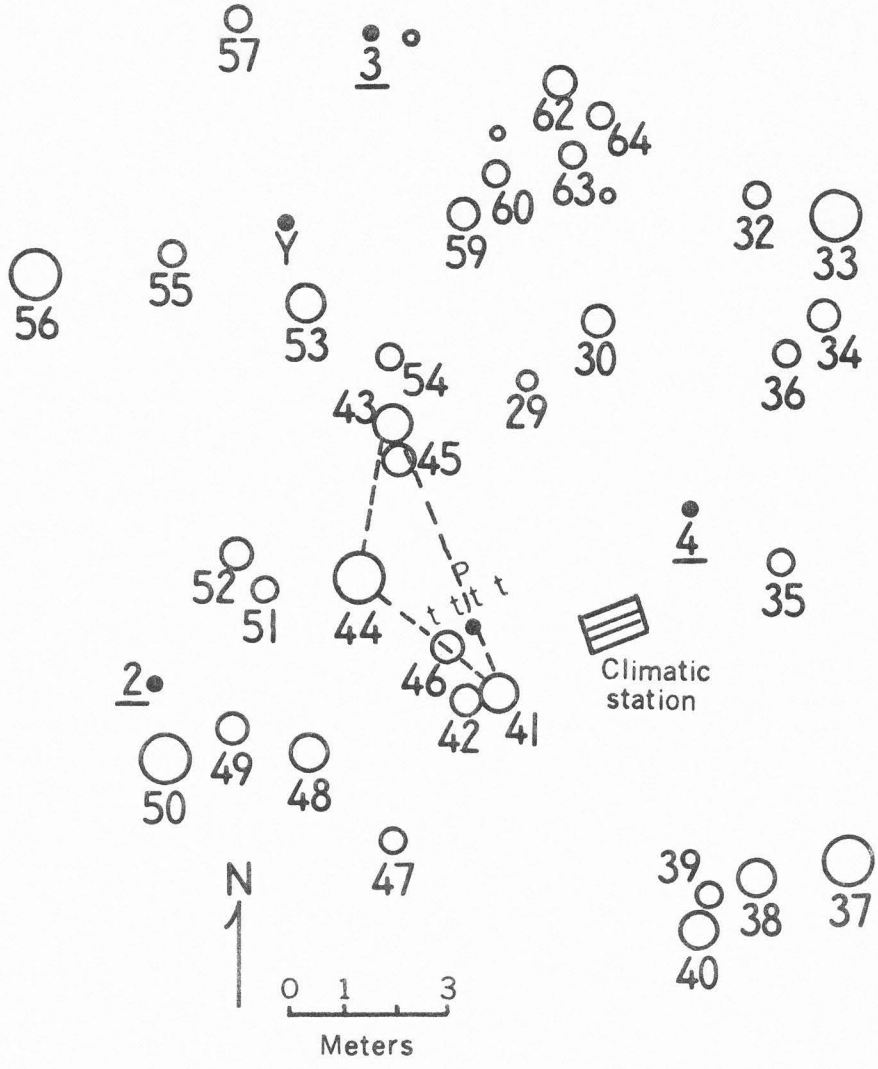
● Neutron probe access tube with an alphabetic or numeric identification code

t Tensiometer

P Soil psychrometer stack at various depths in the soil

○ Tree with numeric identification code. Tree diameter scale is times two. Trees in which thermocouple psychrometers were implaced are connected with a dotted line.

Figure 25. Location of instrumentation and trees at spruce plot 2.



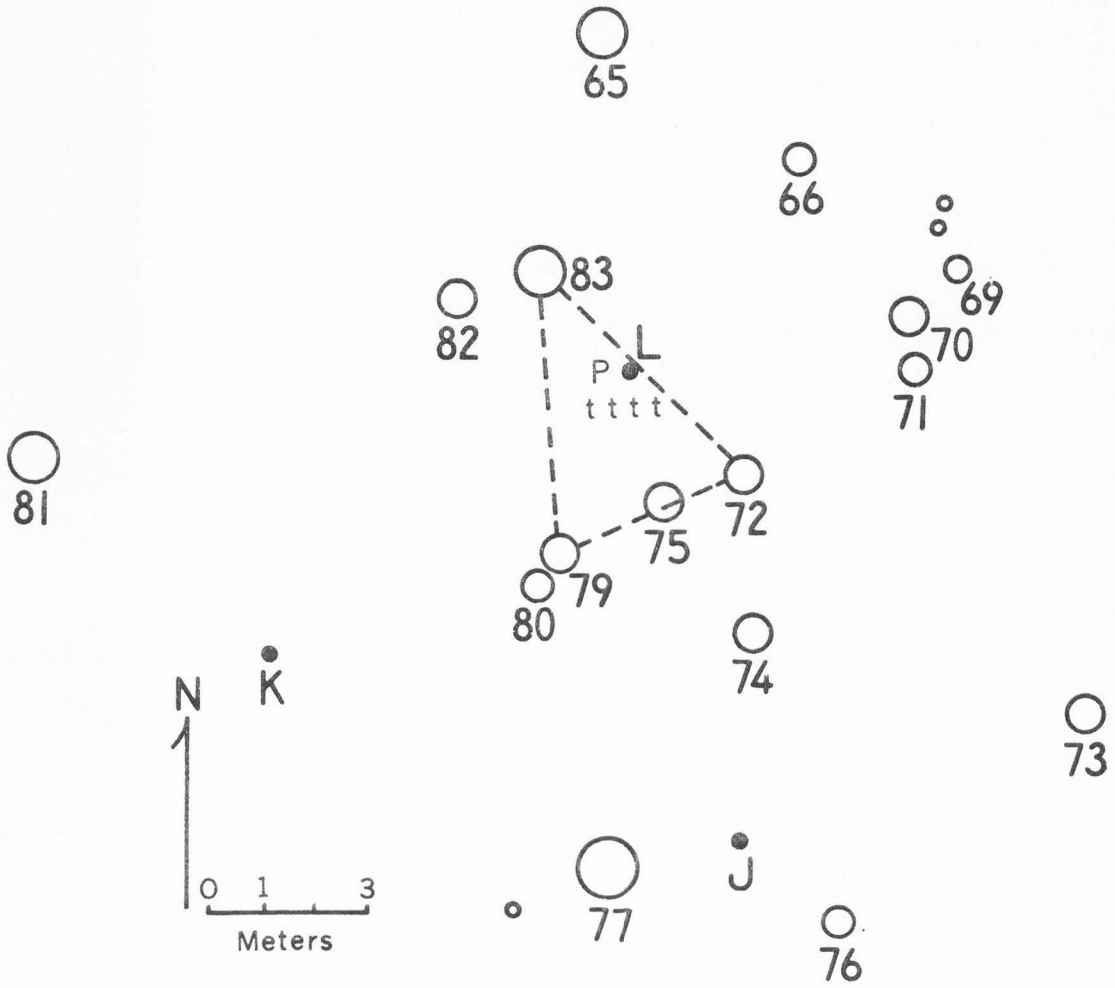
● Neutron probe access tube with an alphabetic or numeric identification code

t Tensiometer

P Soil psychrometer stack at various depths in the soil

◯ Tree with numeric identification code. Tree diameter scale is approximately times two. Trees in which thermocouple psychrometers were implaced are connected with a dotted line

Figure 26. Location of instrumentation and trees at spruce plot 3.



● Neutron probe access tube with an alphabetic or numeric identification code

t Tensiometer

P Soil psychrometer stack at various depths in the soil

◯ Tree with numeric identification code. Tree diameter scale is approximately times two. Trees in which thermocouple psychrometers were implaced are connected with a dotted line

Figure 27. Location of instrumentation and trees at spruce plot 4.

Table 19. Tree height, diameter, and species on the four study plots.

Spruce plot 1

[a]Tree number	Tree height (m)	[b]Tree diameter (cm)	[c]Species
1	24	36	S
2	6	17	S
3	25	54	F
4	16.5	31	S
5	7.5	13	S
6	31.5	70	S
7	15	29	S
8*	22	28	S
9*	27.5	48	S
10*	33	64	S
11	32.5	60	S
12	18.5	27	S
13	13	24	S
14	7.5	14	S
15	6	12	F
16	15	23	S

Spruce plot 2

17*	13	27	S
18	--	--	S
19	--	--	S
20*	--	37	S
21*	37.5	49	S
22	33	51	S
23	34.5	55	S
24	--	15	F
25	27	15	S
26	34.5	59	S
27	34	42	S
28	38	63	S

Table 19. Continued.

Spruce plot 3

[a]Tree number	Tree height (m)	[b]Tree diameter (cm)	[c]Species
29	5	7	S
30	13	16	S
31	3.5	5	S
32	7.5	11	S
33	29.5	47	F
34	10	19	S
35	5	8	S
36	8	10	S
37	35	54	S
38	23	31	S
39	7	15	S
40	33.5	45	S
41*	38	45	S
42	21.5	25	S
43*	35	43	S
44*	39	70	S
45	15	22	F
46	15.5	19	S
47	6	10	S
48	32	33	S
49	21	28	S
50	37	60	S
51	9	15	S
52	27	26	S
53	29	37	S
54	4	14	S
55	8	11	F
56	35	52	S
57	16	21	S
58	4	7	S
59	13	16	S
60	6	13	S
61	2.5	4	S
62	7.5	20	S
63	8	10	S
64	6	8	S

Table 19. Continued.

Spruce plot 4

[a]Tree number	Tree height (m)	[b]Tree diameter (cm)	[c]Species
65	30.5	54	S
66	11	22	S
67	5.5	9	S
68	28.5	5	S
69	5.5	16	S
70	27.5	38	S
71	23	28	S
72*	29.5	41	S
73	33	41	S
74	31	43	S
75	29	33	S
76	9	18	S
77	32	95	S
78	2	1	S
79*	27	42	S
80	21	29	S
81	30.5	70	S
82	22	32	S
83*	28	59	S

[a]Trees with asterisks are those in which thermocouple psychrometers were implaced.

[b]Diameter at breast height.

[c]S = Engelmann spruce (Picea engelmannii)
F = Subalpine fir (Abies lasiocarpa)

Appendix D

Water Potential Prediction Regressions for Single Junction Peltier Psychrometers

Table 20. Regression analysis of predicted water potential, regression #1.

Source variation	Degrees freedom	Mean square	F-ratio	Fractional R^2
Total	127	182.45		
Microvolts	1	40.64	17.51**	0.037
Millivolts	1	5.10	2.20*	
$(\text{Microvolts})^2$	1	29.01	12.50**	0.472
$(\text{Millivolts})^2$	1	3.27	1.41	
$(\text{Microvolts} \times \text{Millivolts})_2$	1	6.01	2.59*	
Microvolts x $(\text{Millivolts})_2$	1	3.02	1.30	
Millivolts x $_2$(Microvolts)	1	9.74	4.20**	0.190
$(\text{Millivolts})^2 \times (\text{Microvolts})^2$	1	4.61	1.99	0.018
Model	8			0.988
Error	119	2.32		

**Significant at the $\alpha = 0.01$ level
*Significant at the $\alpha = 0.05$ level

Table 21. Regression analysis of predicted water potential, regression #2.

Source variation	Degrees freedom	Mean square	F-ratio	Fractional R^2
Total	123	207.04		
Microvolts	1	44.88	16.55**	0.871
Millivolts	1	4.03	1.49	
$(\text{Microvolts})^2$	1	13.89	5.12**	0.033
$(\text{Millivolts})^2$	1	1.93	0.71	
(Microvolts x Millivolts)	1	3.03	1.12	
Microvolts x $(\text{Millivolts})^2$	1	0.49	0.18	
Millivolts x $(\text{Microvolts})^2$	1	7.72	2.85**	0.067
$(\text{Millivolts})^2$ x $(\text{Microvolts})^2$	1	5.26	1.94	0.014
Model	8			0.988
Error	115	2.71		

Table 22. Regression analysis of predicted water potential, regression #3.

Source variation	Degrees freedom	Mean square	F-ratio	Fractional R^2
Total	71	102.82		
Microvolts	1	26.99	2.20	0.757
Millivolts	1	0.04		
$(\text{Microvolts})^2$	1	5.91	0.48	
$(\text{Millivolts})^2$	1	0.003		
(Microvolts x Millivolts)	1	3.11	0.25	0.135
Microvolts x $(\text{Millivolts})^2$	1	0.89	0.07	
Millivolts x $(\text{Microvolts})^2$	1	4.61	0.38	
$(\text{Millivolts})^2$ x $(\text{Microvolts})^2$	1	3.65	0.30	
Model	8			0.894
Error	63	12.24		

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Candidate for the Degree of

Doctor of Philosophy

Dissertation: Internal Water Potential of an Engelmann Spruce Stand in Relation to Soil and Atmospheric Factors

Major Field: Watershed Science

Personal Data

Date and place of birth: August 12, 1946, Erie, Pennsylvania.
Citizenship: United States
Sex: Male
Status: Single

Academic and Practical Experience by Date

Summer 1964, light construction work; Summer 1965, recreation aid, U. S. Forest Service; Summer 1967, forestry aid, U. S. Forest Service; Summer 1968, research assistant, Utah State University; 1968-71, National Science Foundation Trainee, Utah State University; 1971-72, research assistant, Utah State University; 1972-73, lecturer, Forest Science Department, Utah State University.

Computer Languages

Fortran IV

Degrees Held or Expected

B.S., Forest Watershed Management, Utah State University, 1968.
Ph.D., Watershed Science, Utah State University, 1973.

Experience With Computing Systems

IBM System 360
UNIVAC 1108
Burroughs 6700
WANG 600 series

Hobbies

Painting, photography, auto mechanics and electronics

Honoraries, Professional Societies, Other Awards

Xi Sigma Pi, Phi Kappa Phi, Society of American Foresters, American Forestry Association, Water Pollution Control Federation (Utah Section), Paul and Neva Dunn Scholarship Award, National Science Foundation Fellowship.

Papers and Publications

1969. Manipulating Gambel oak and aspen for water savings in central Utah. Paper given at the Annual Meeting of the Intermountain Section, Society American Foresters, Logan, Utah.

1972. Calibration of thermocouple psychrometers: a suggested procedure for development of a reliable predictive model. In R. W. Brown and B. P. Van Haveren (eds.), Psychrometry in water relations research. Utah Agricultural Experiment Station, in press.